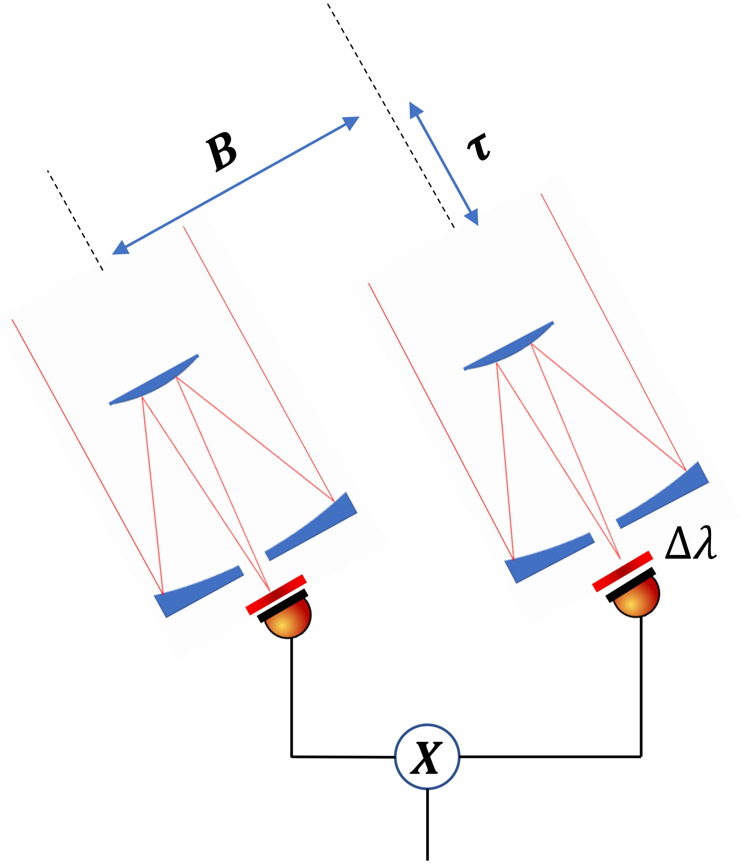
Utilizing state of the art technologies for a modern stellar intensity interferometer:

recent results and ongoing developments of the I2C instrument

Nolan Matthews

Institut de Physique de Nice

Intensity interferometry for astronomical observations



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$$g^{(2)}(\tau = 0, B) = \frac{\langle I_1(t) I_2(t, B)\rangle}{\langle I_1(t)\rangle\langle I_2(t)\rangle} = 1 + |V(B)|^2$$

$$V(B) \propto FT[I(\alpha)]$$

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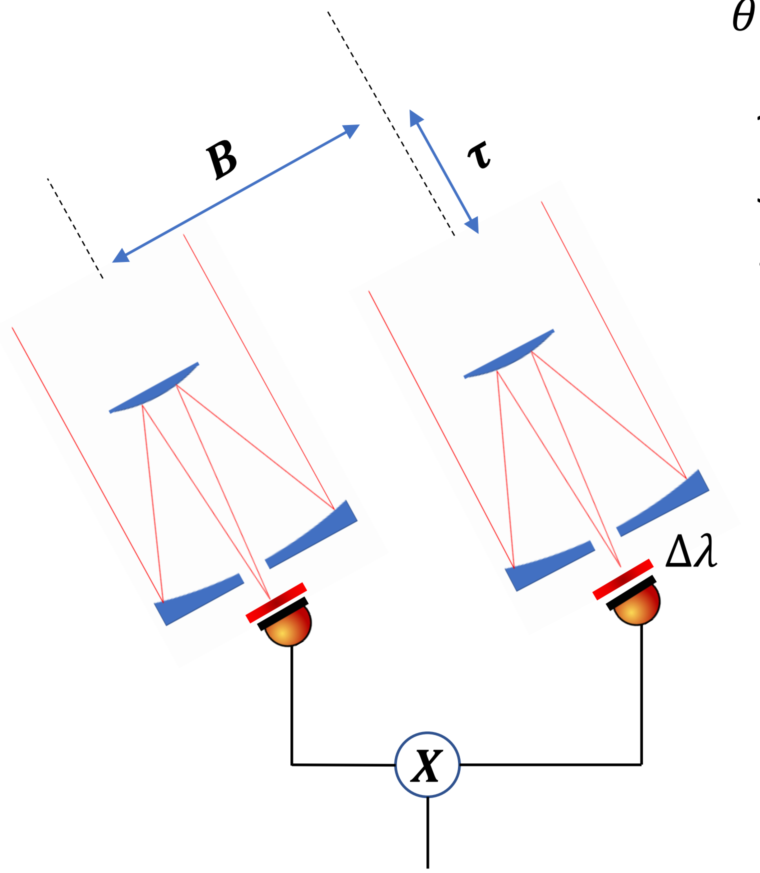

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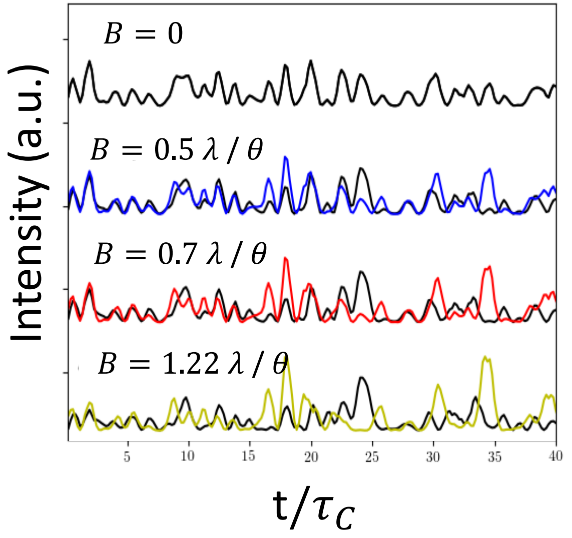

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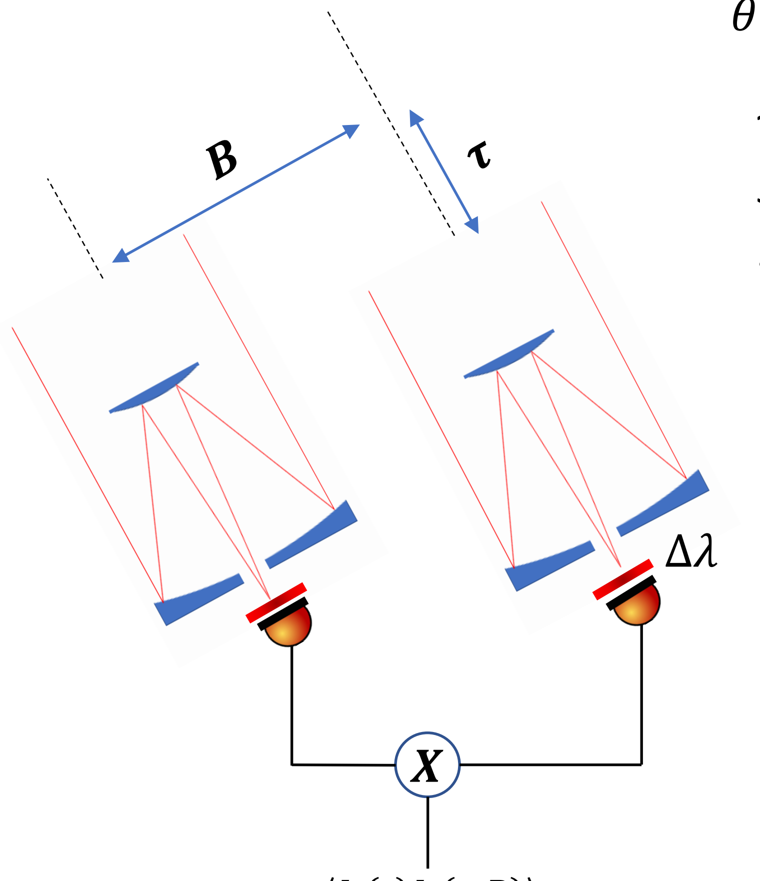

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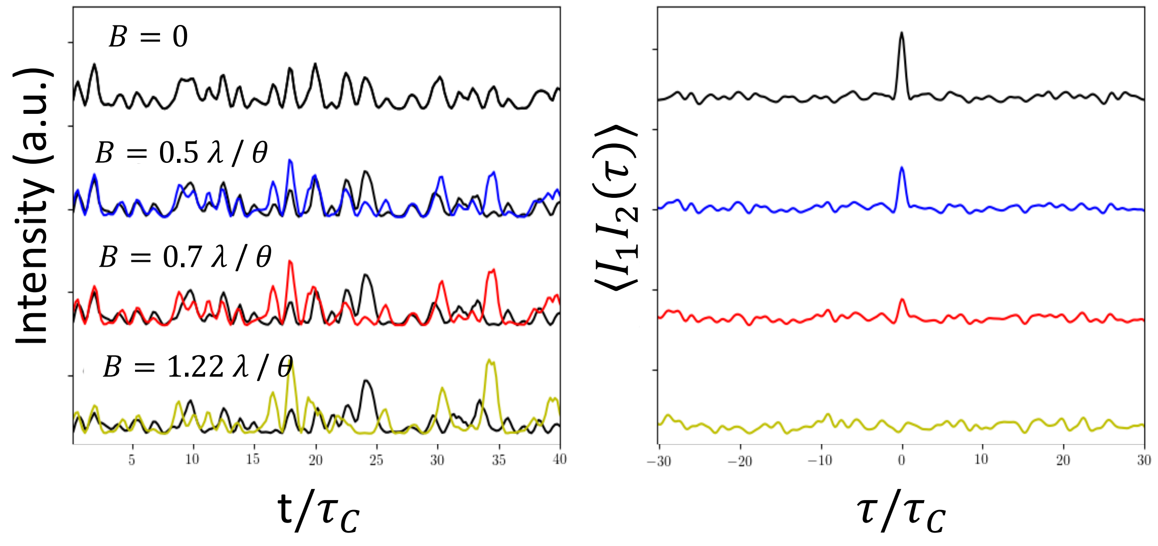

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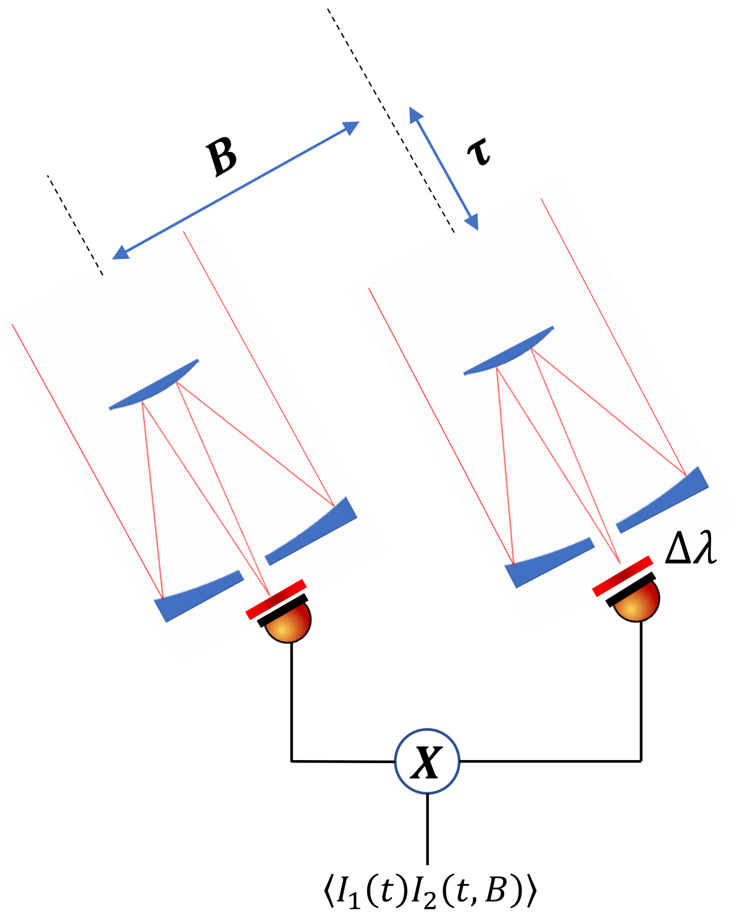

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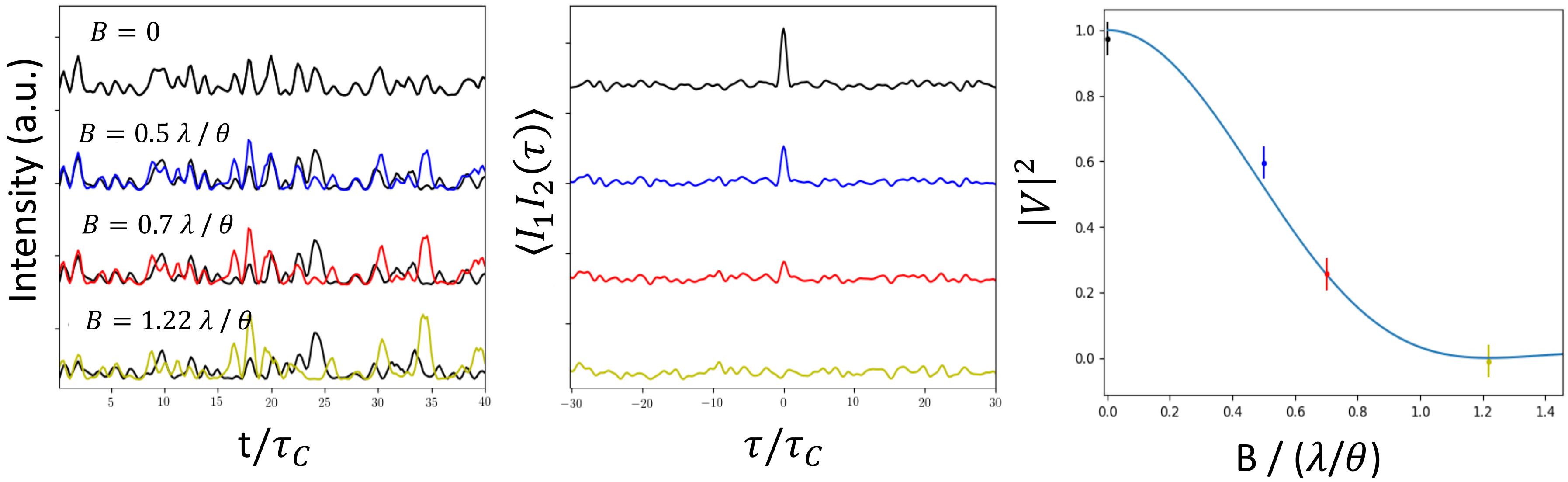

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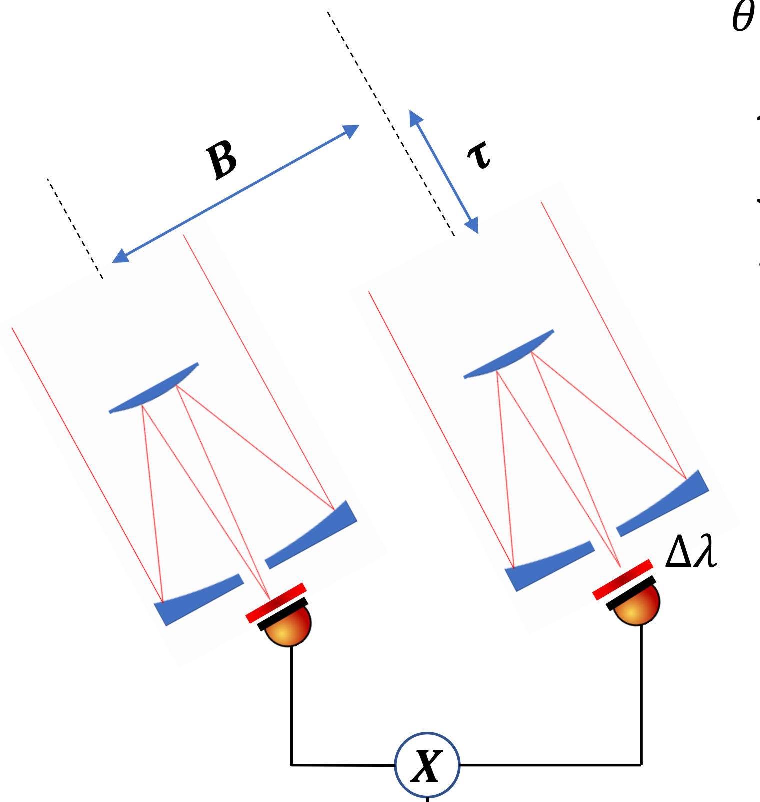

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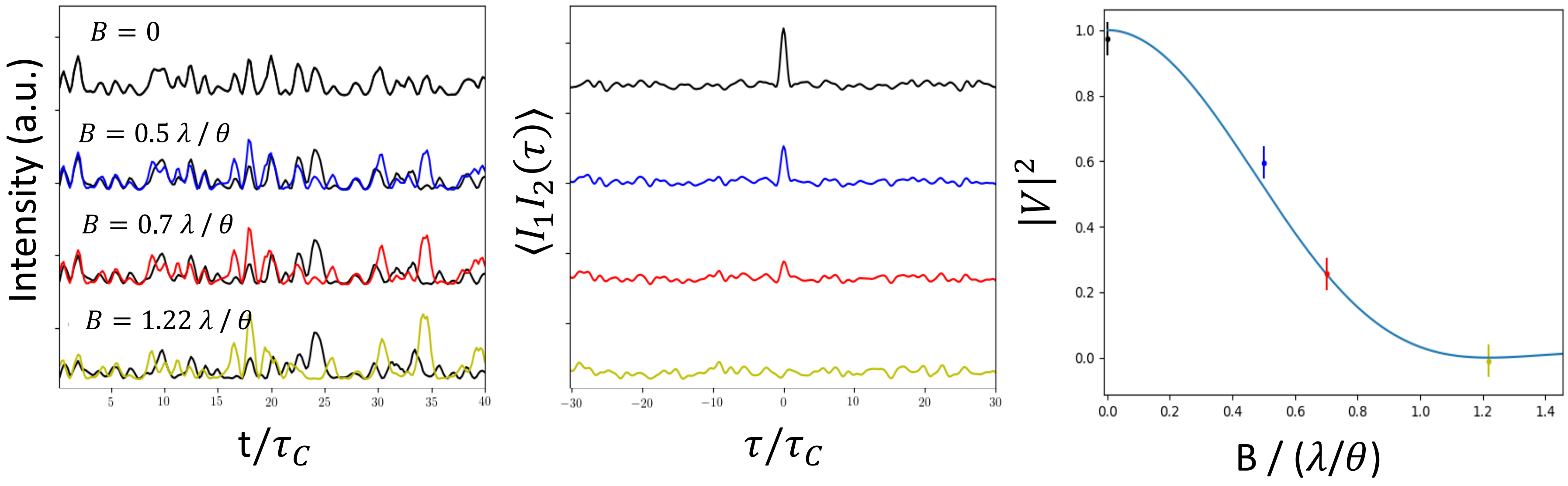

$\tau_C \sim \left(\frac{c}{\lambda^2}\Delta\lambda\right)^{-1}$ → For $\lambda = 500$ nm / $\Delta\lambda = 1$ nm, $\tau_C < 1$ picosecond! → $g^{(2)}(\tau=0,B) \sim 1 + \frac{\tau_c}{\tau_d}|V(B)|^2$

Even with the fastest detectors (**10s of picoseconds**) we average over many coherence times!

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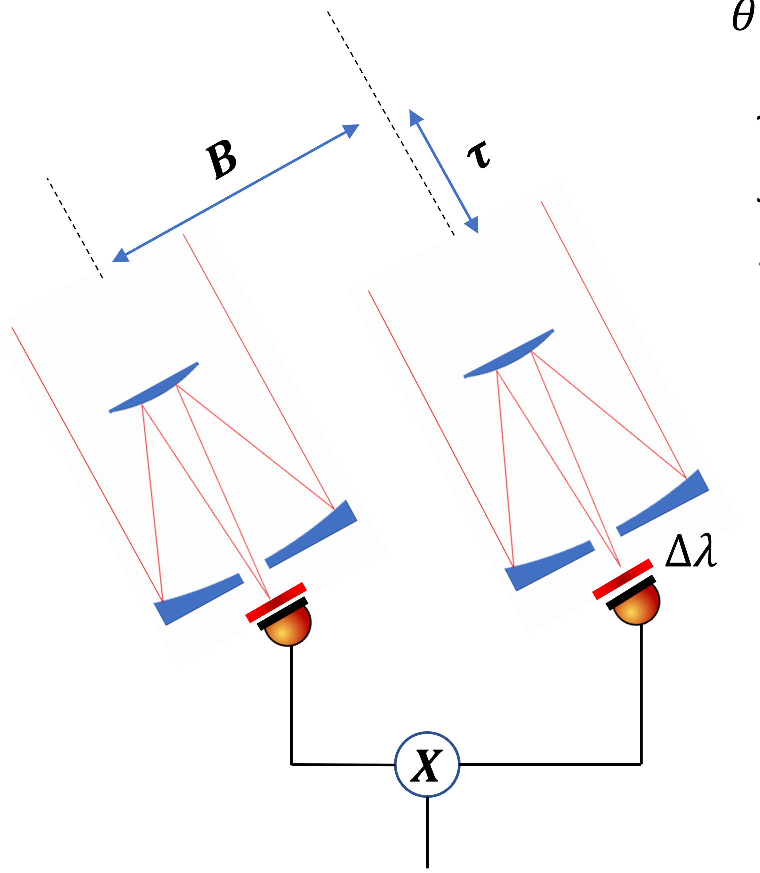

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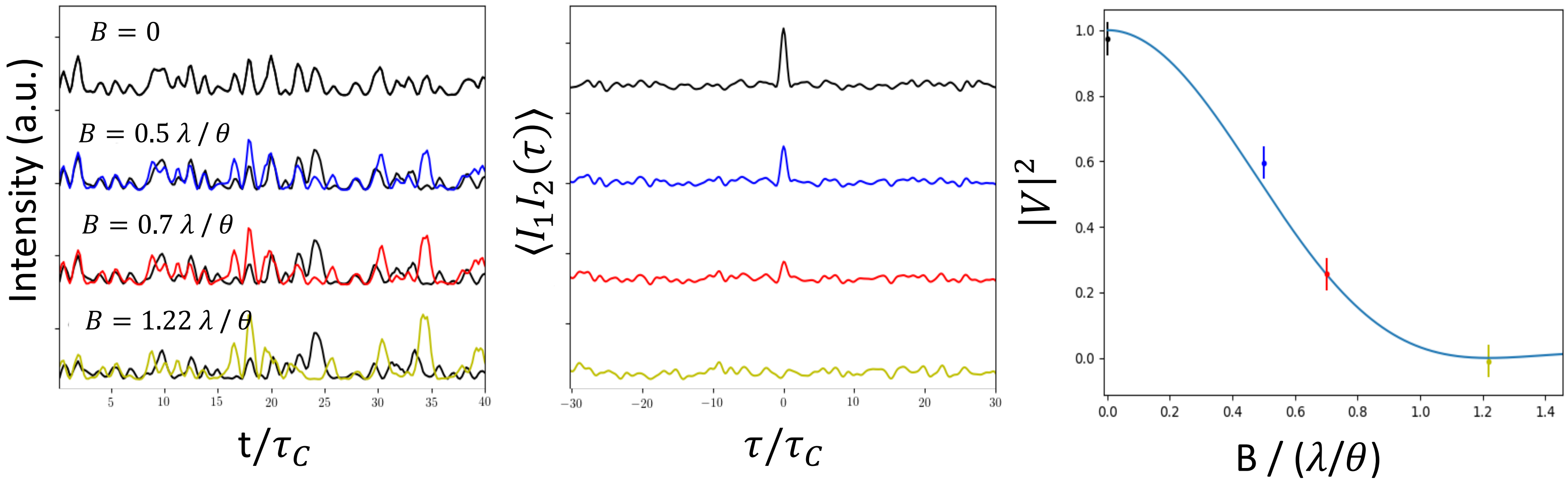

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→ Sensitivity degraded but **tolerant to path length fluctuations**

→ **Insensitive** against atmospheric turbulence. Can operate at **short optical wavelengths** (e.g. 350 – 800 nm, B, V, R, I bands)

→ Enables "distributed" systems = **scaling to many telescopes + long baselines**

I2C Consortium

INPHYNI “Cold Atom” Team

Robin Kaiser | William Guerin | Mathilde Hugbart | Guillaume Labeyrie

Nolan Matthews

Former members:
Antoine Dussaux
(Post-doc UNS, 2015-2016)
Antonin Siciak
(PhD student UCA, 2018-2021)

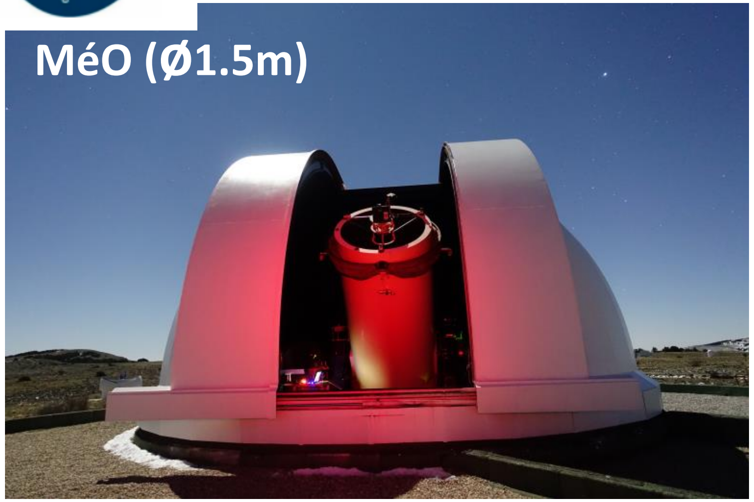
Lagrange (OCA)

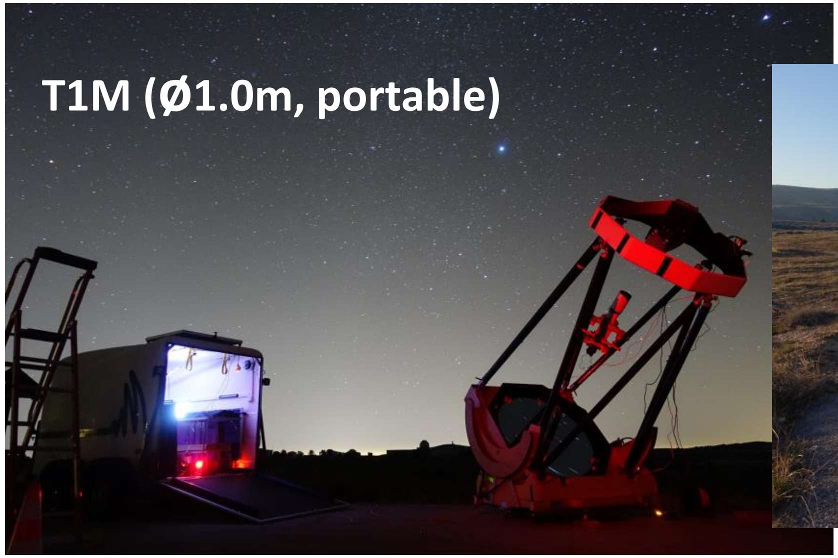
Jean-Pierre Rivet | Farrokh Vakili | Olivier Lai | Armando Domiciano de Souza | David Vernet

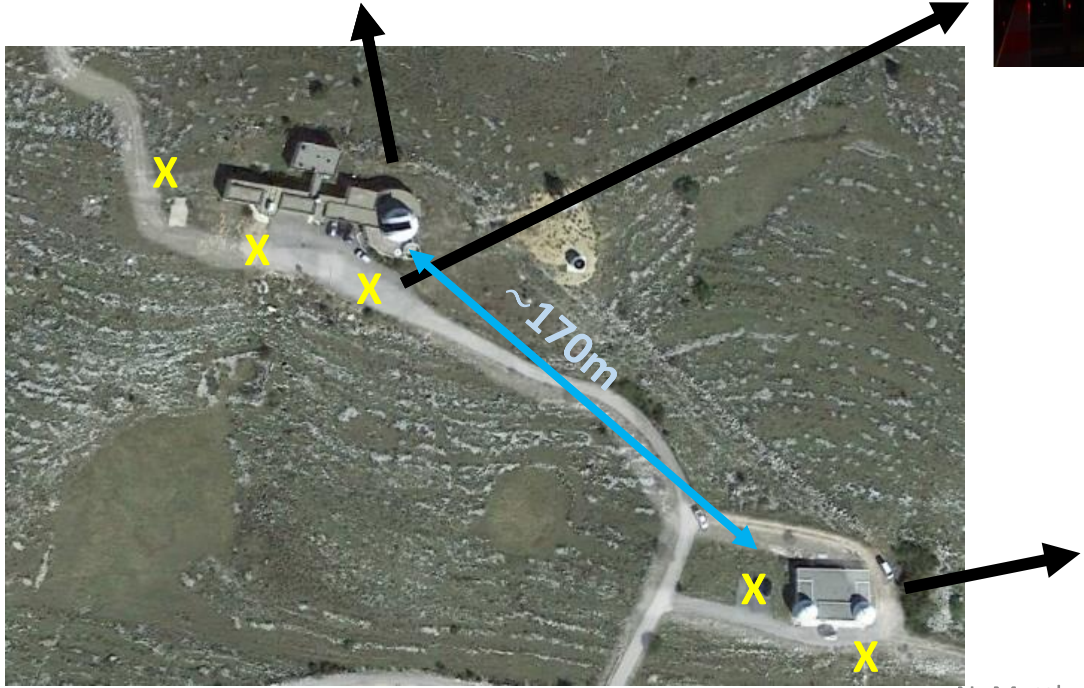
Géoazur, MéO team

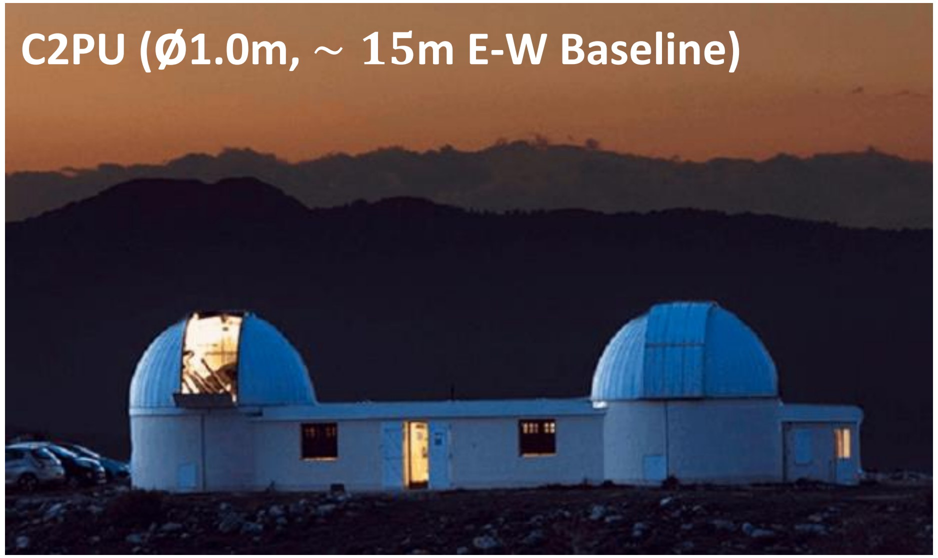
Clément Courde | Julien Chabé

Intensity Interferometry Facilities at Calern

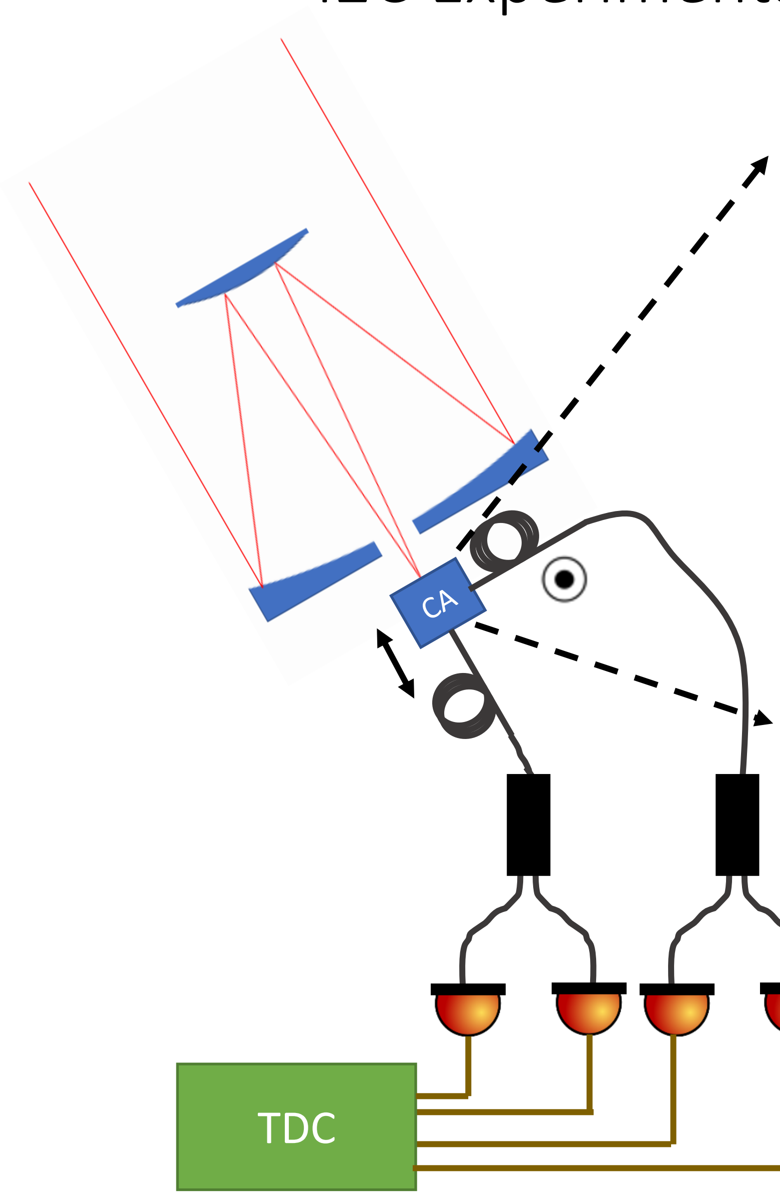


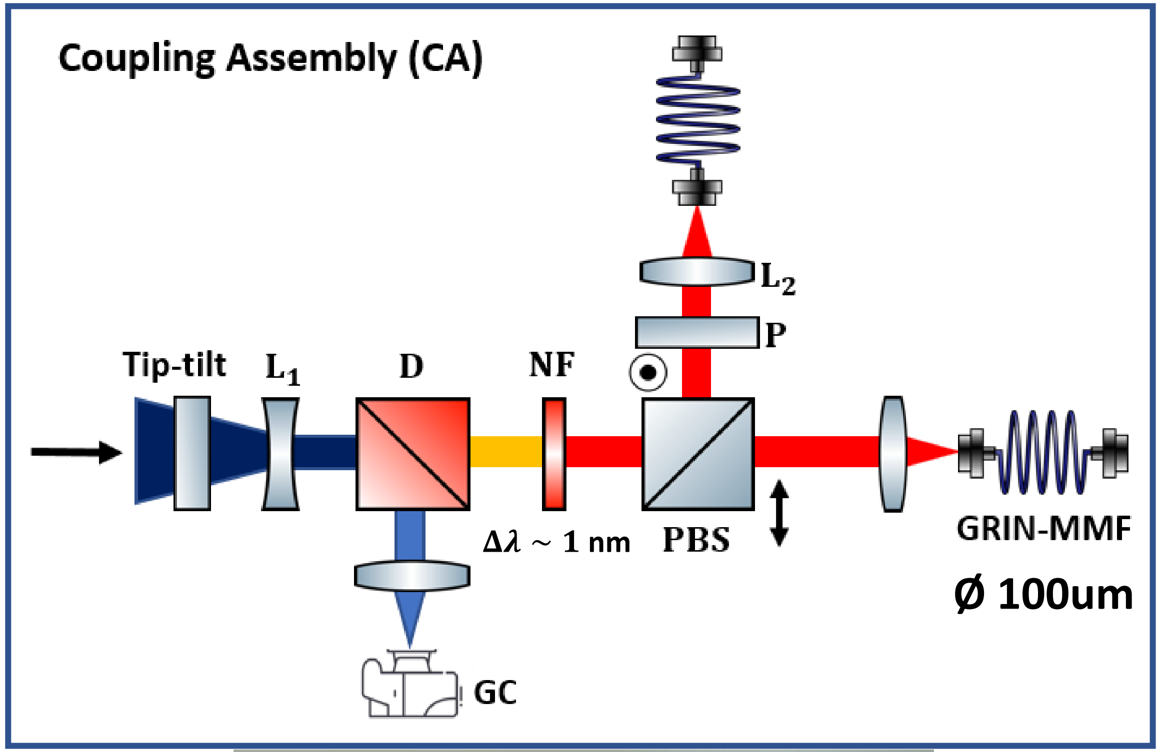


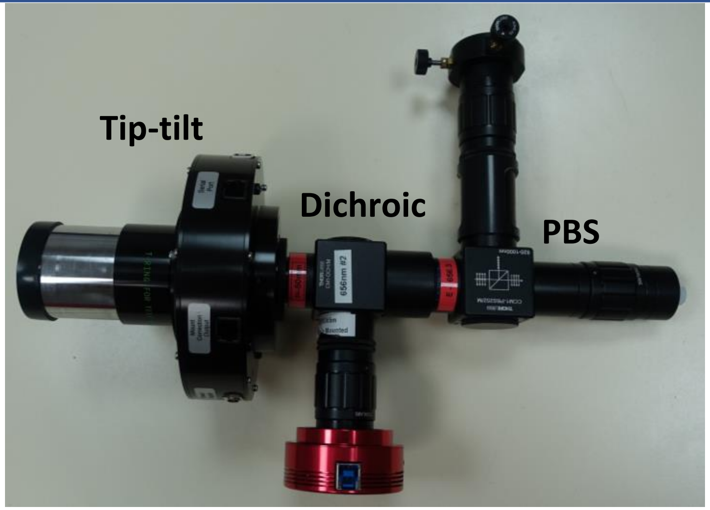




I2C Experimental Setup







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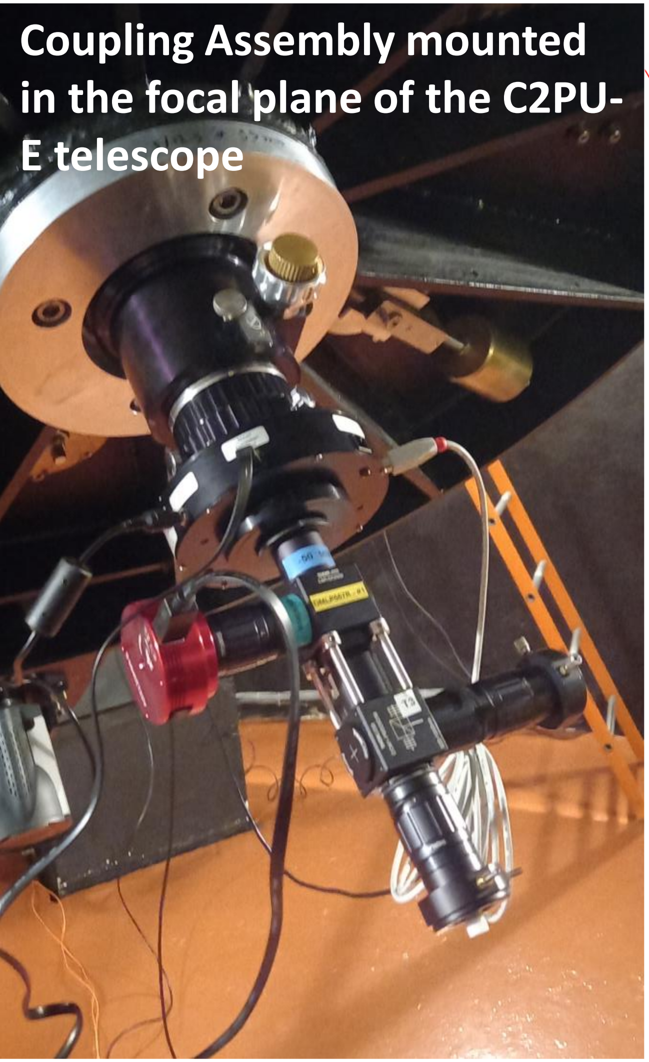

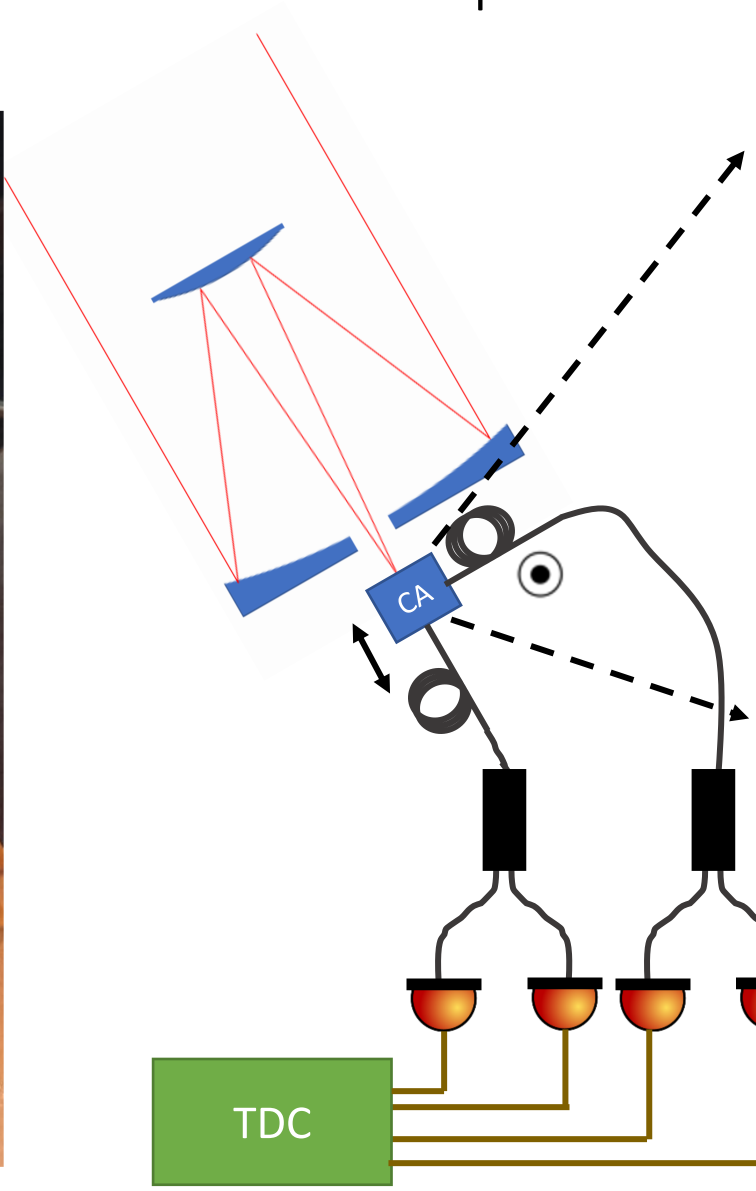

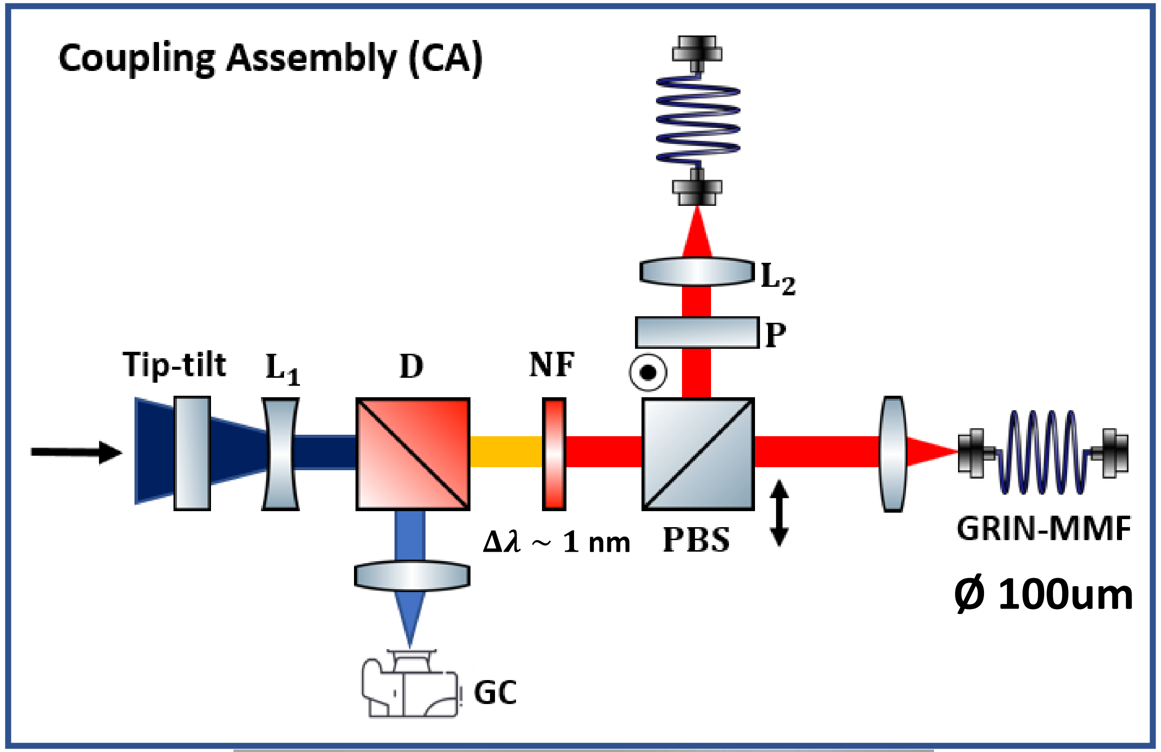

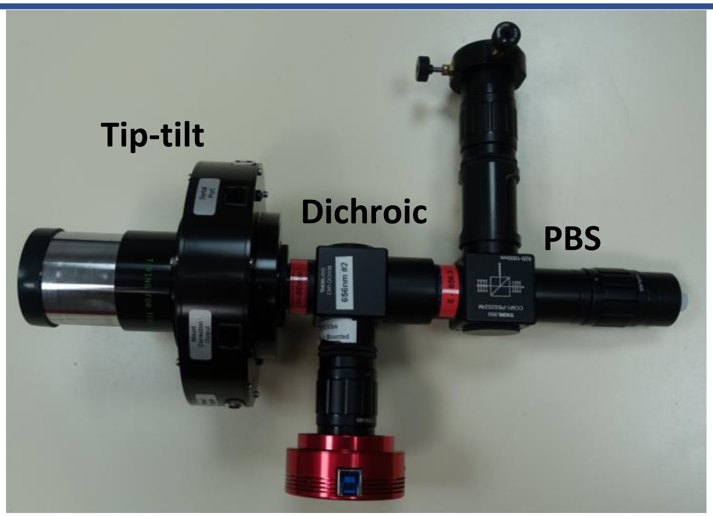

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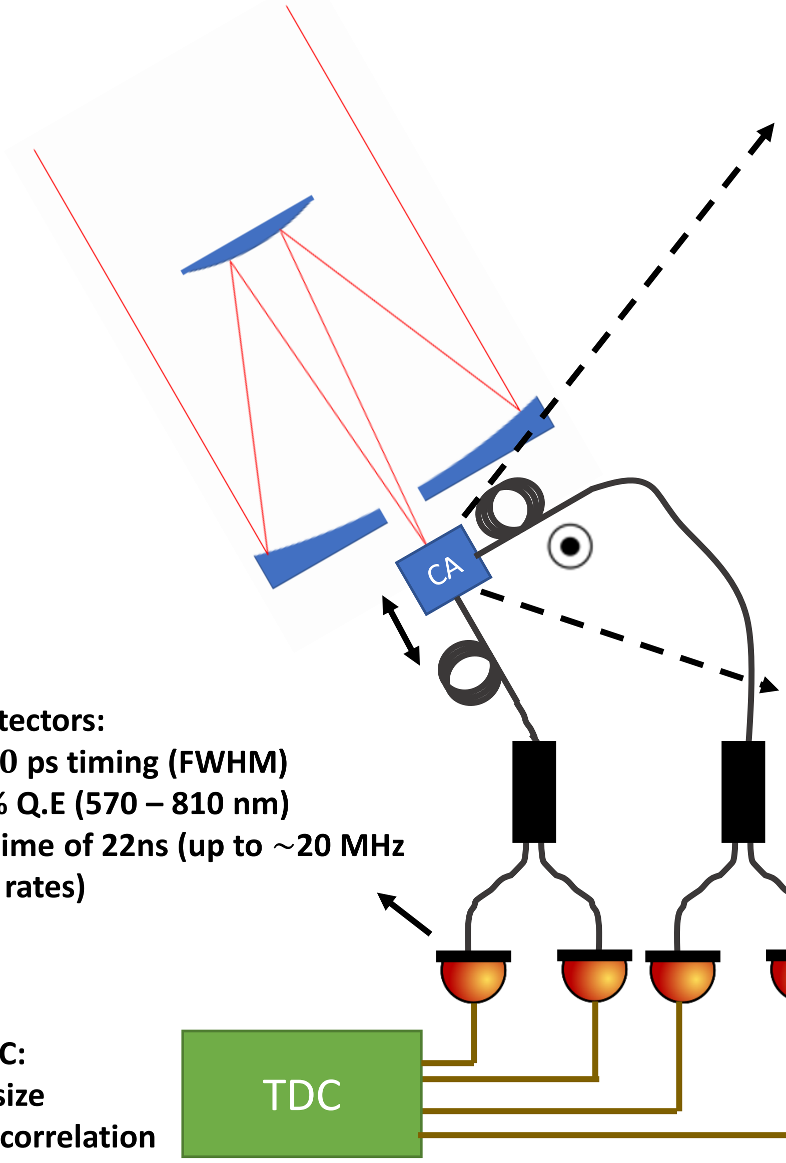
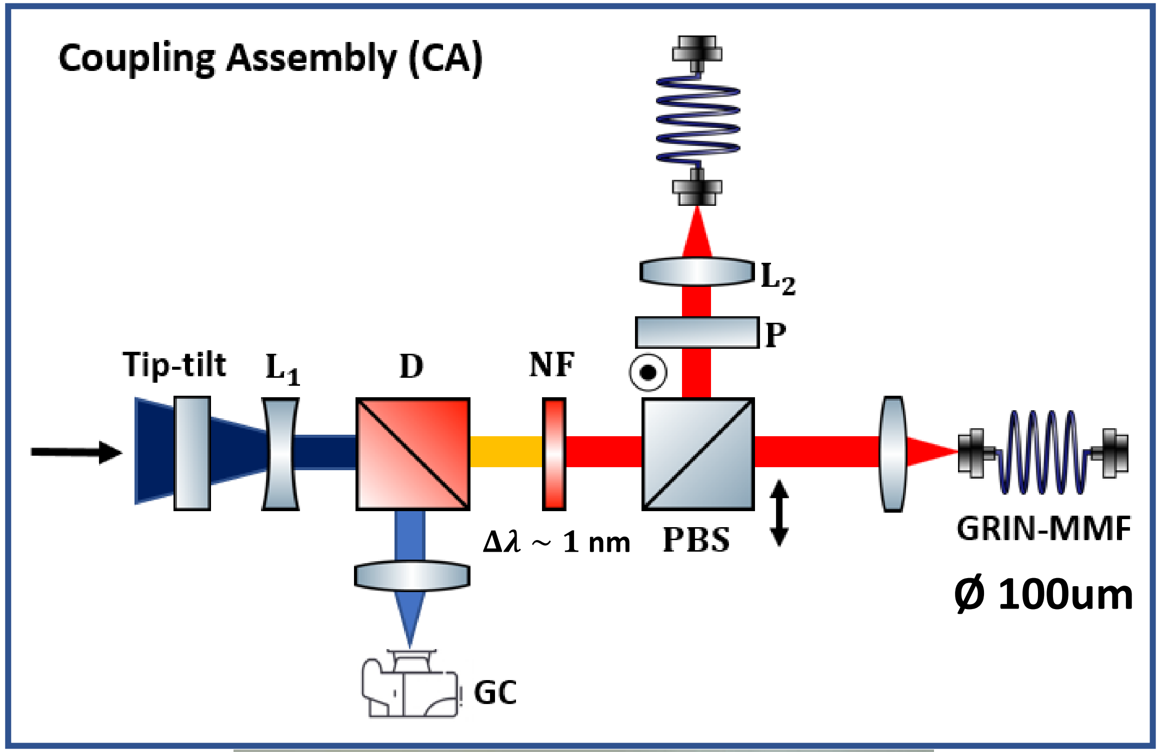


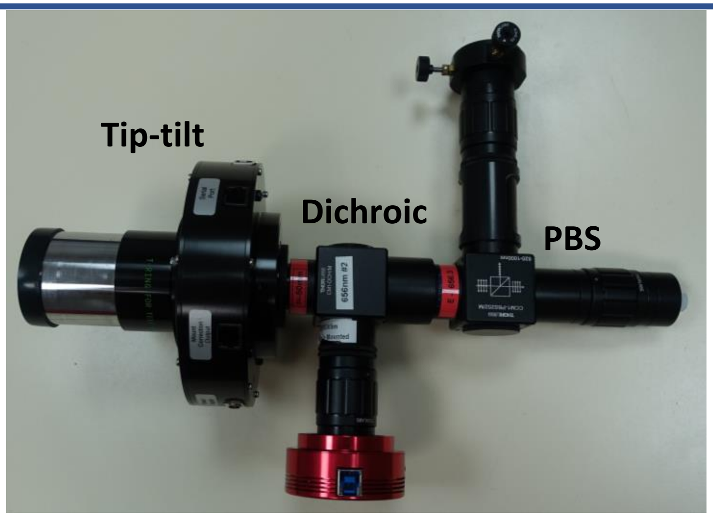


SPAD detectors:

- $\sim$ 700 ps timing (FWHM)
- > 60% Q.E (570 – 810 nm)
- Deadtime of 22ns (up to ~20 MHz count rates)

High speed TDC:

- 10 ps bin-size
- Real-time correlation



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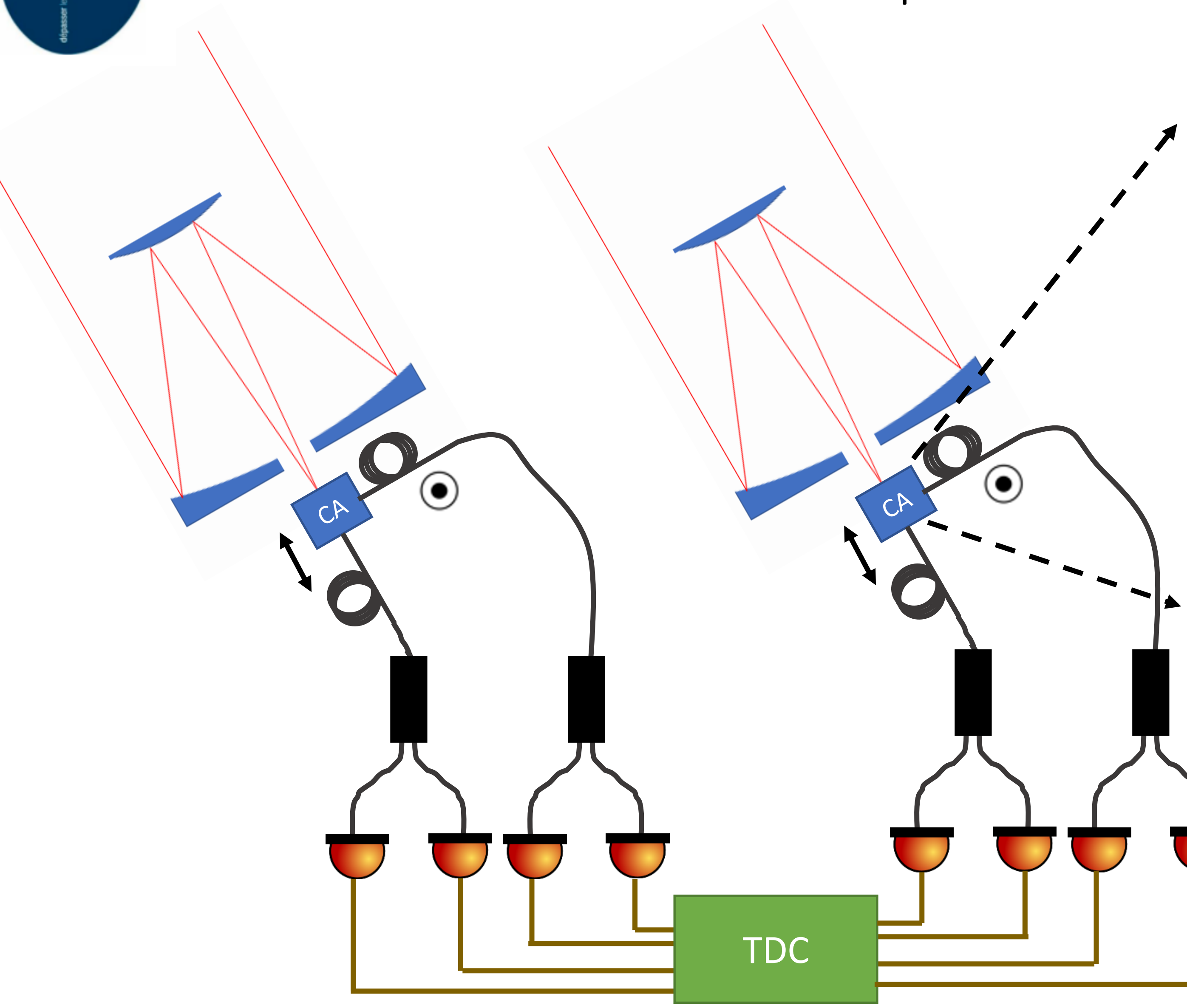
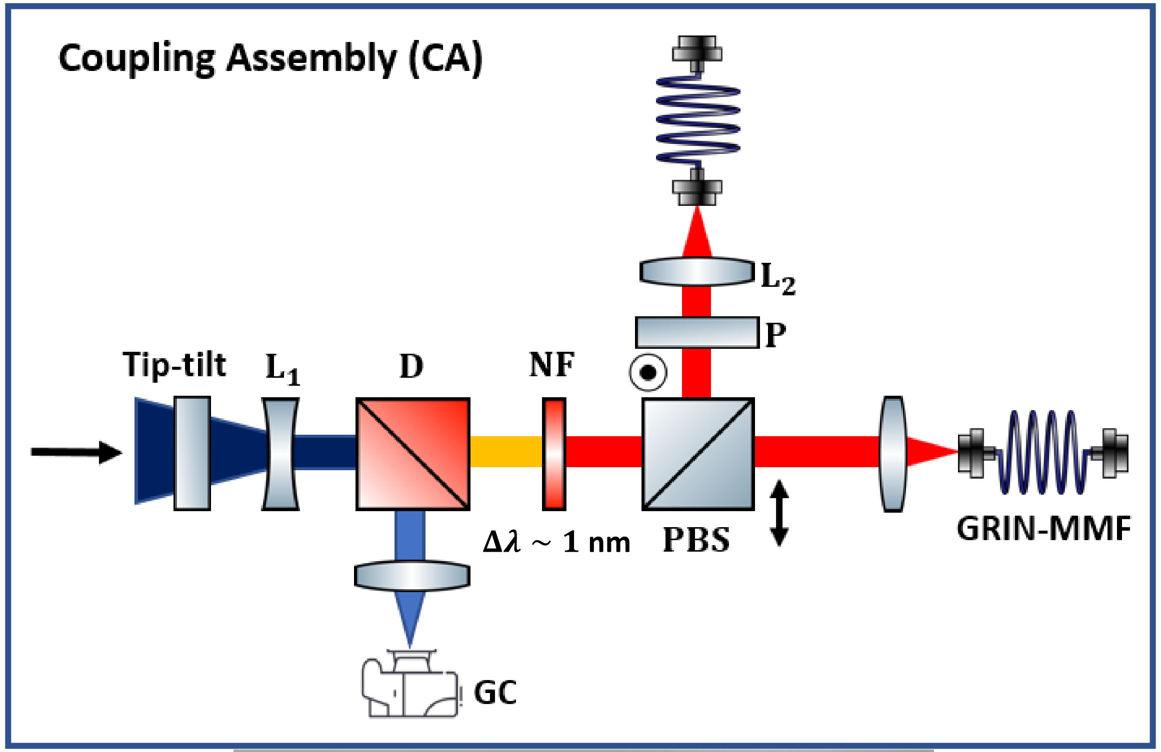
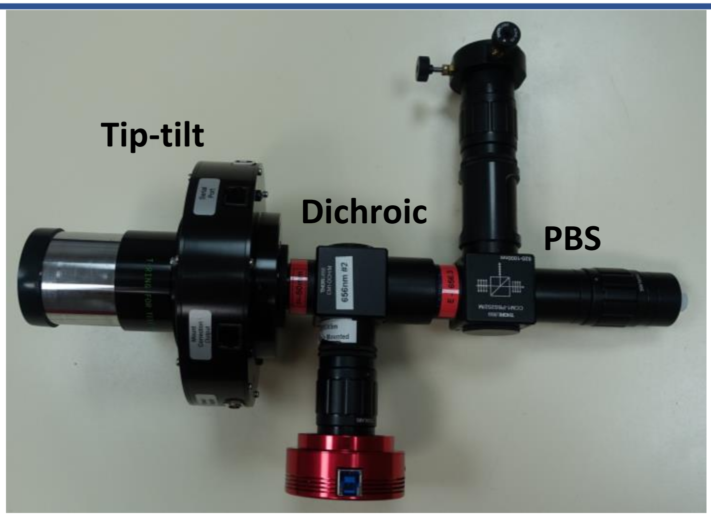
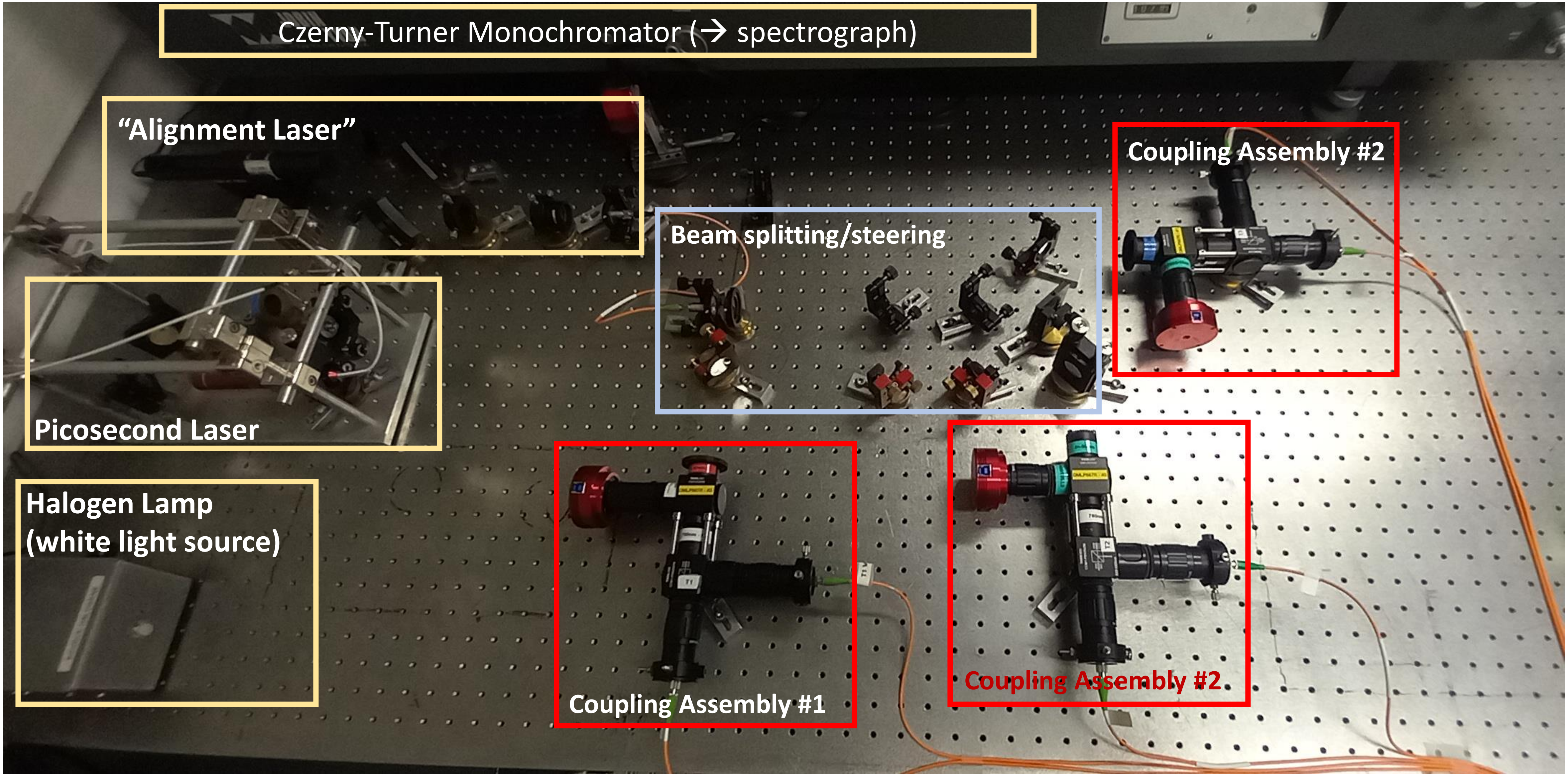






Laboratory Bench for Characterization Tests



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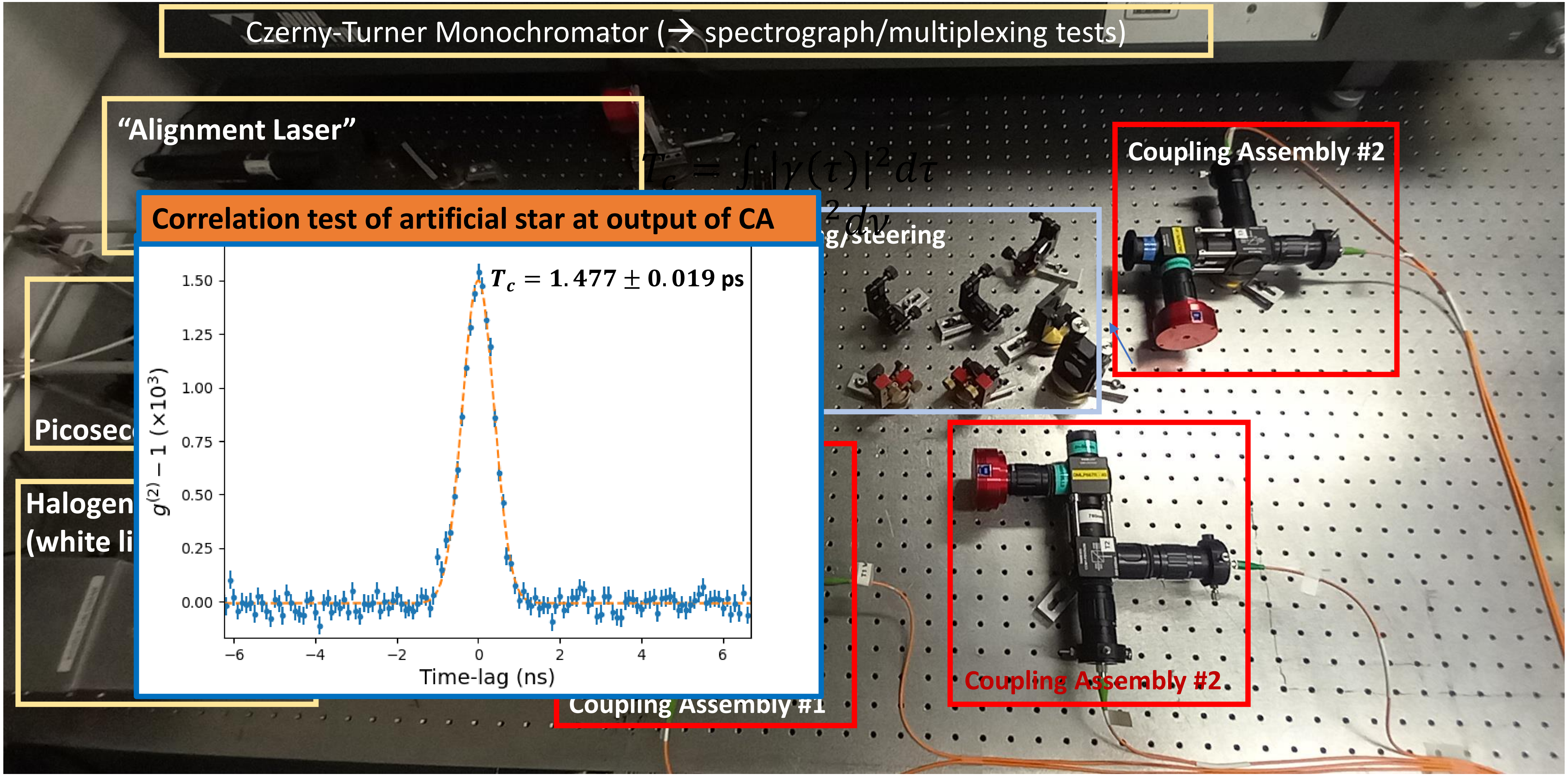

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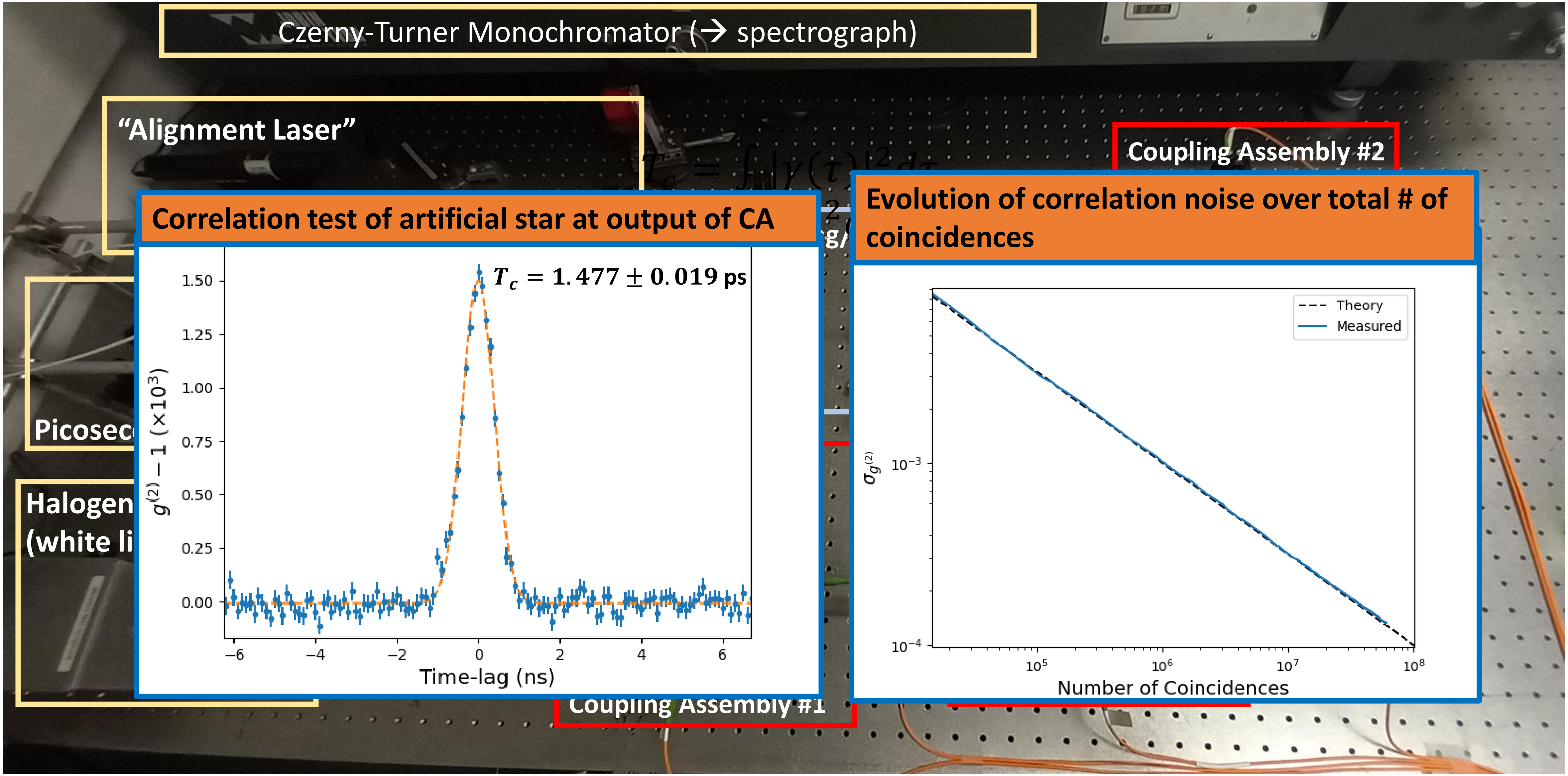
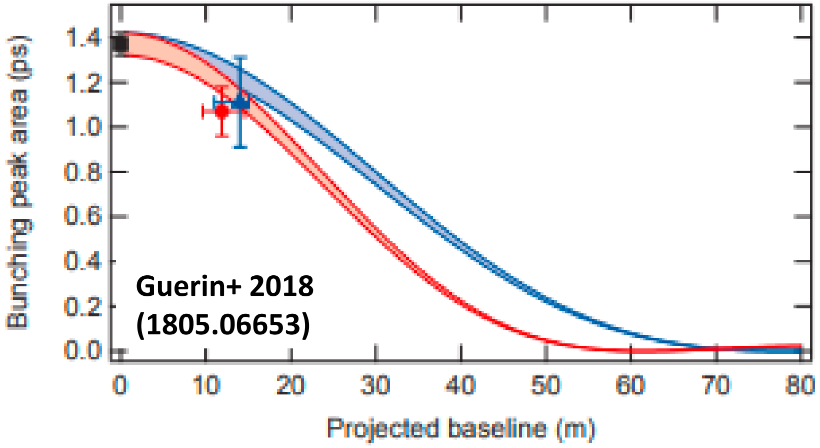
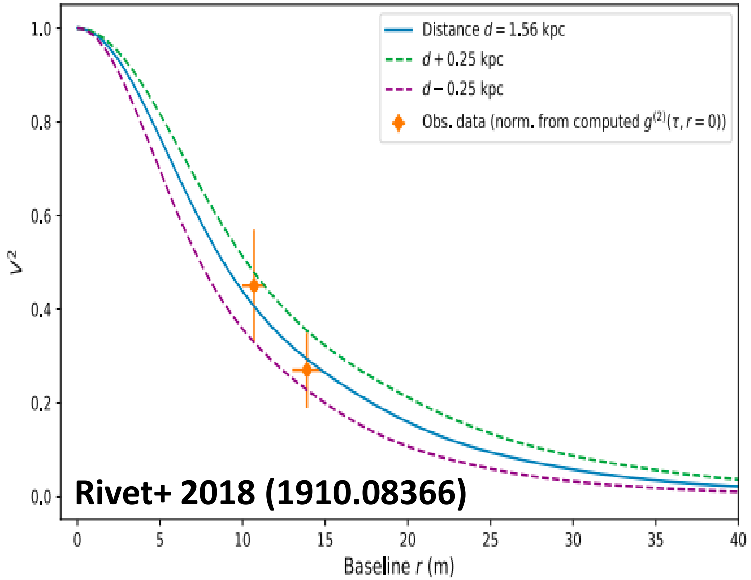


Highlighted scientific results from I2C @ Calern

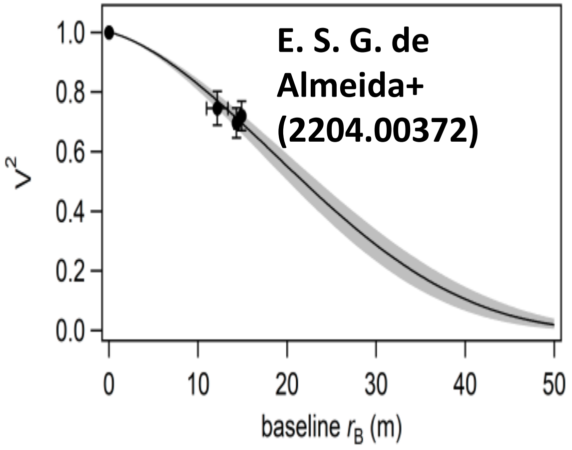
Spatial Intensity Correlations

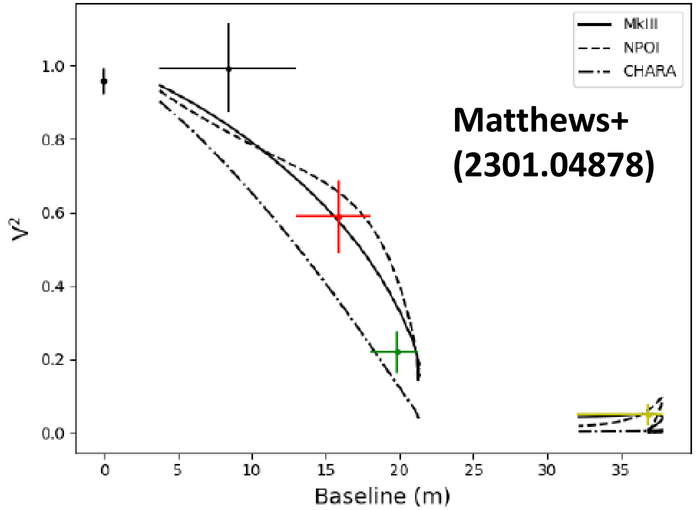


Distance calibration to P Cyg

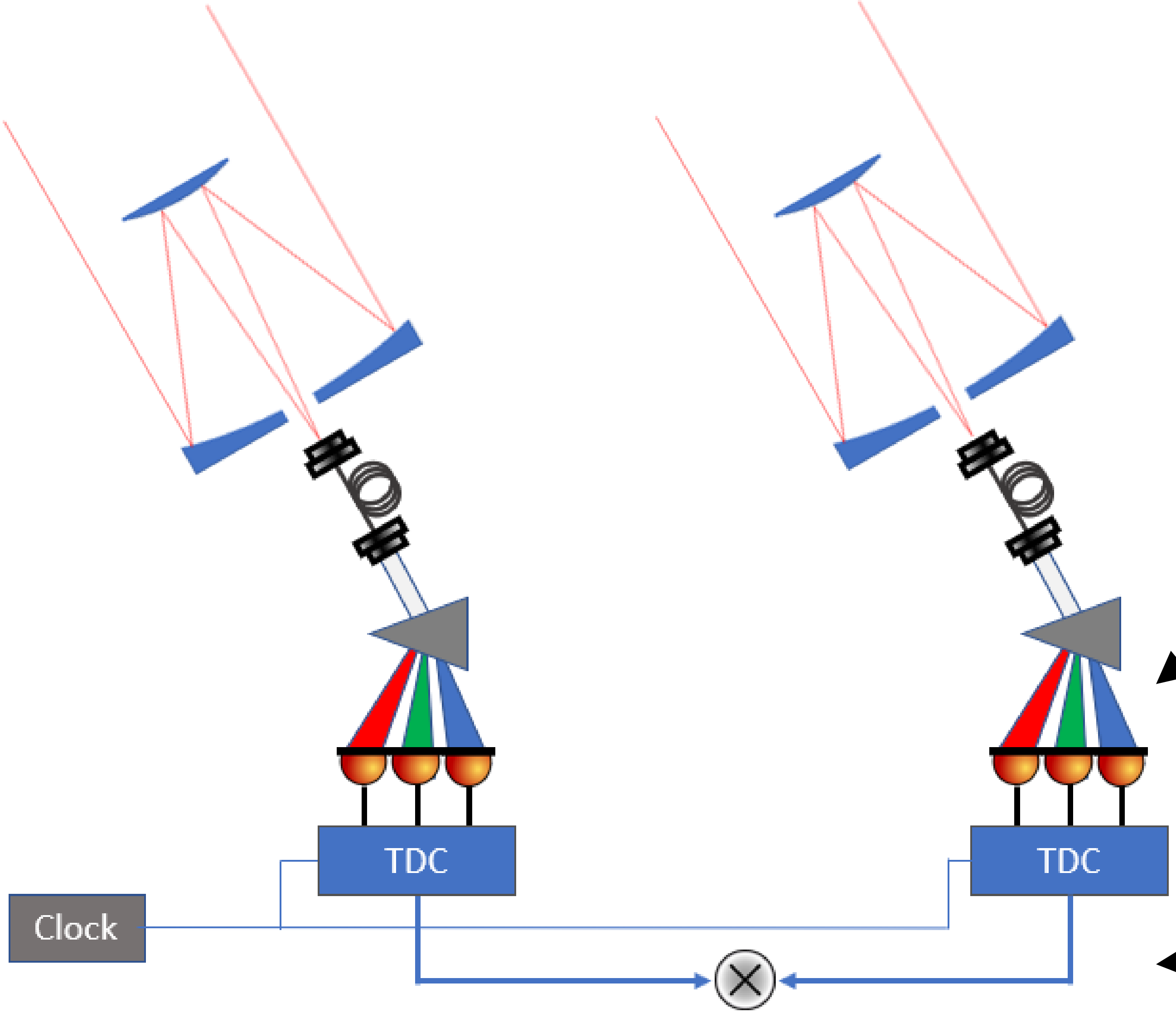


Observations of Rigel





Future work:
towards spectral multiplexing and state of the art detectors

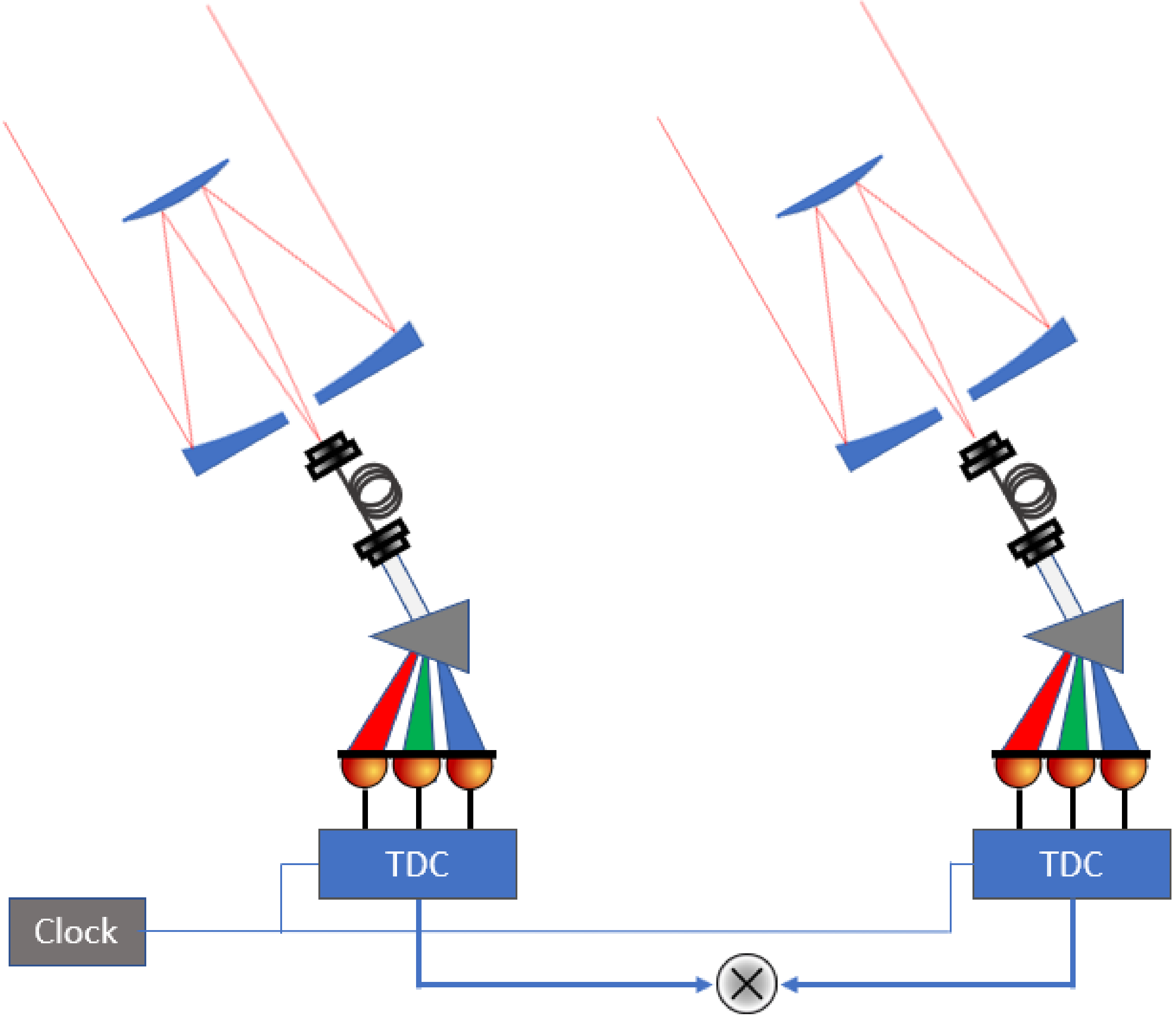


Spectral multiplexing improves sensitivity by $\sqrt{N_{ch}}$

Time-tagging of individual photon events (synchronized by common clock) enables scalable system (i.e. many telescopes!)

Correlation can be performed post-observation

Future work:
towards spectral multiplexing and state of the art detectors



Utilize superconducting nanowire single photon detectors (SNSPDs):

- < 20 ps jitter
- > 80% quantum efficiency

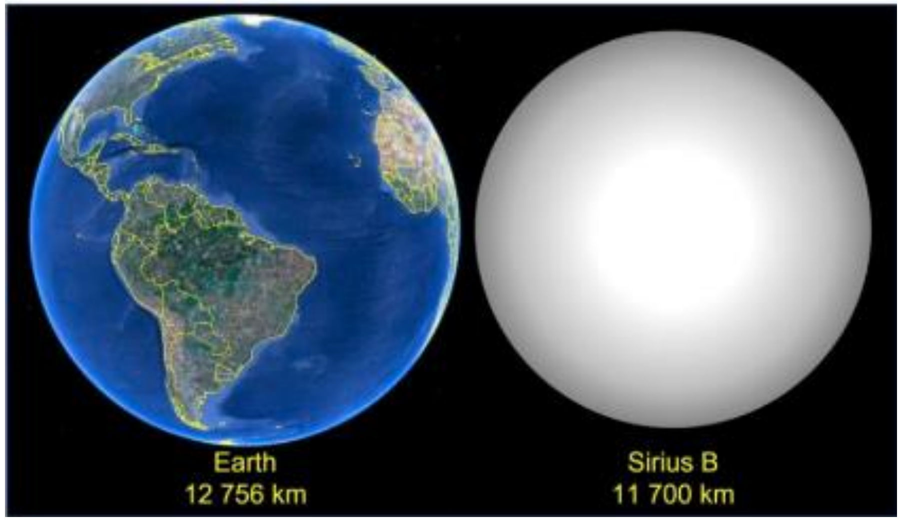
Sensitivity increase:
- x6 from time-resolution
- x4 for spectral multiplexing (16 channels)
- Modest improvement from quantum efficiency

- Large telescopes?
  - ➢ x64 for 8m vs 1m diameter telescopes

➔ Characterize targets brighter than 8th or 9th magnitude in 1 night observation

➔ Precision measurements (σ_{V^2} < 0.1%) of bright targets in < hourly timescales

A way to directly measure the diameter of Sirius B?



- Angular diameter of ~ 30 uas → need kilometric-scale baselines at visible wavelengths
- Stellar magnitude within reach with proposed sensitivity improvements.
- Received letter of support from Keck, CHFT, and Institute for Astronomy – University of Hawaii
- ERC grant proposal submitted….

Summary

- I2C project → intensity interferometry using optical telescopes paired with **modern technologic capabilities**
  - **complementary** to approaches using Cherenkov telescopes.

- Currently exploring ways of substantially improving sensitivity to enable **novel science** and **expand wavelength coverage** and capabilities of optical interferometry.

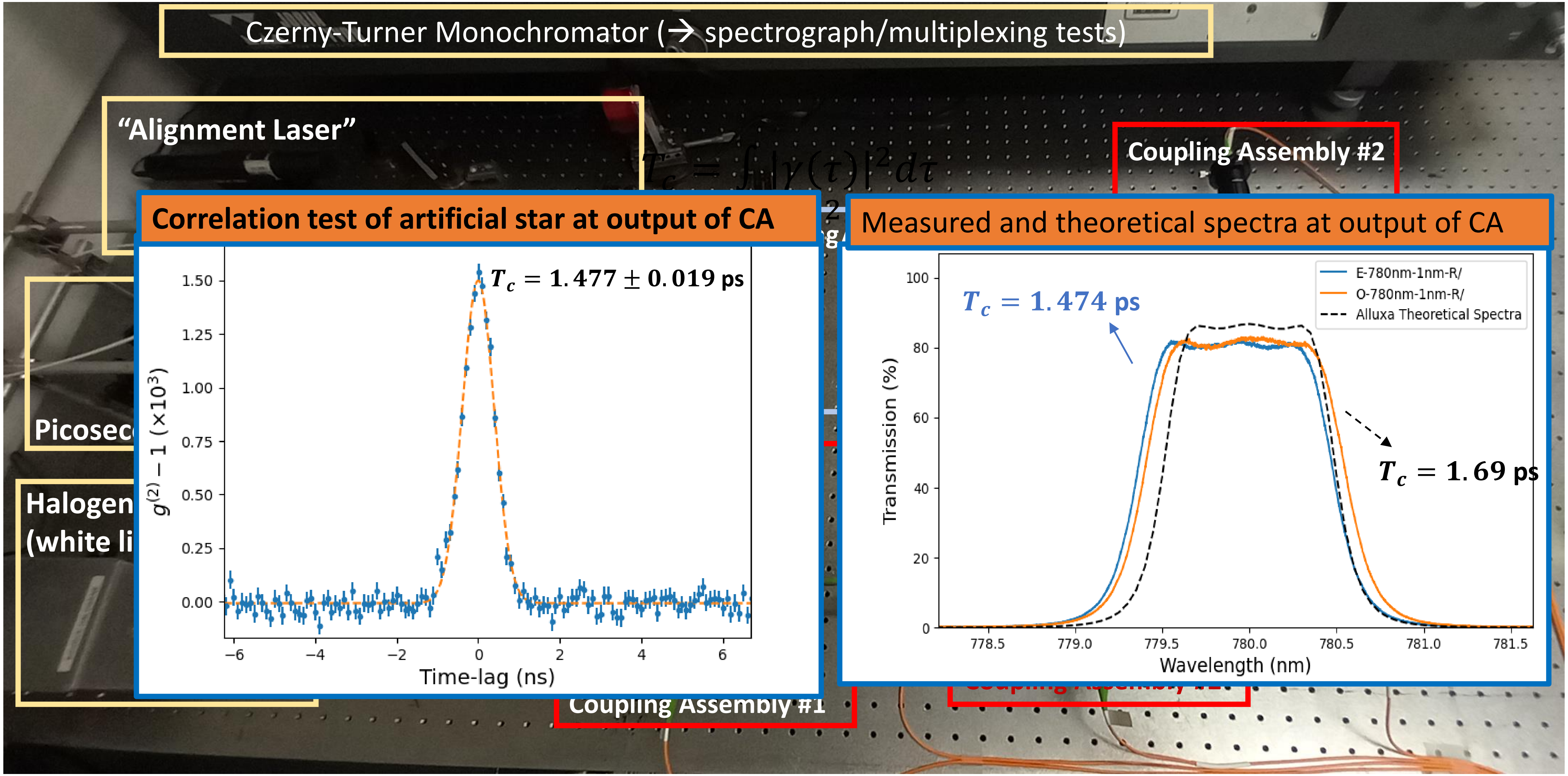
- **Demonstrated on-sky results** with both regional (Calern) and international (e.g. VLTI) observatories illustrating **portability and robustness** of the technique

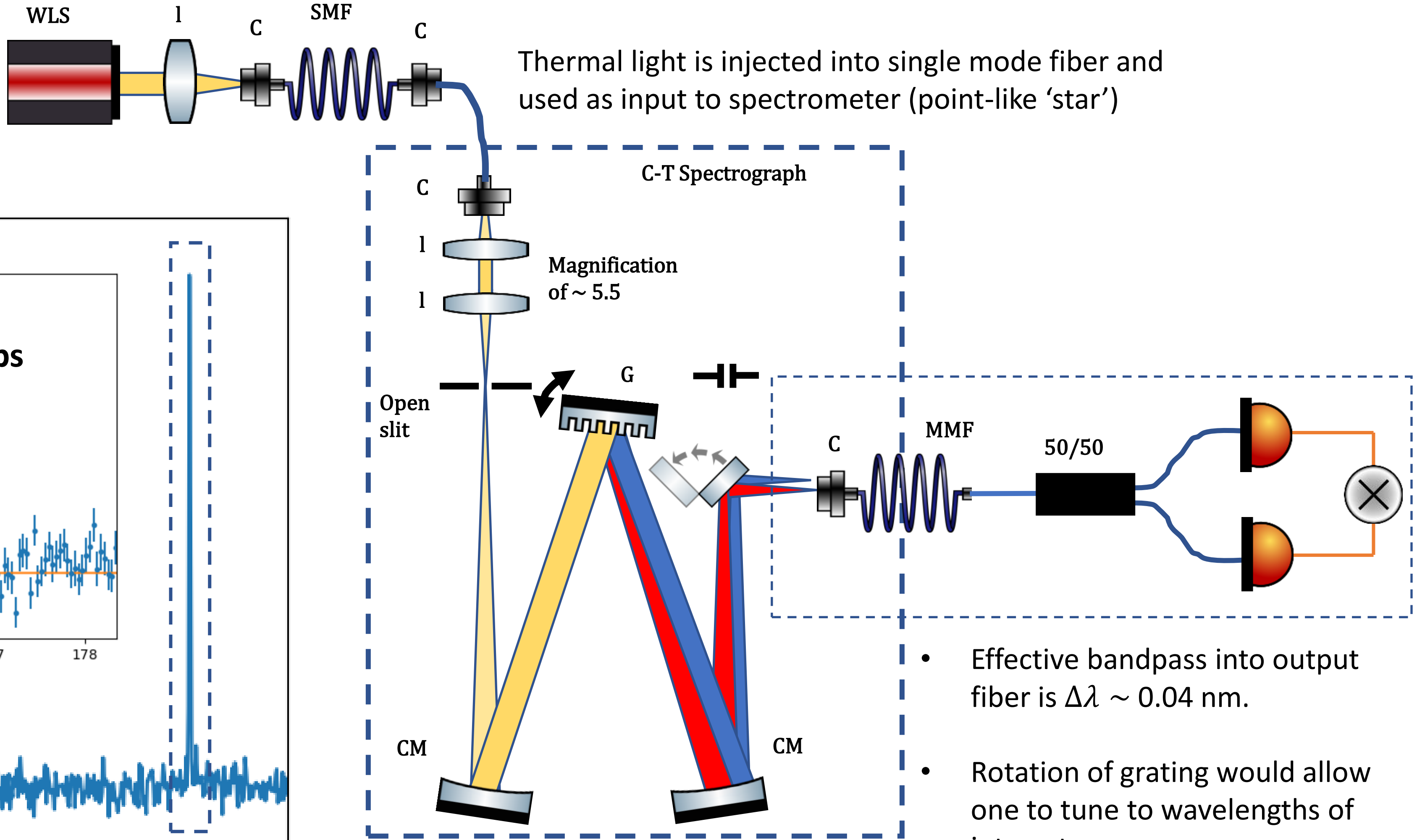
Opportunities available (Ph.D. / post-doc)!

Contact William Guerin (william.guerin@univ-cotedazur.fr) or Robin Kaiser (robin.kaiser@univ-cotedazur.fr) for details.

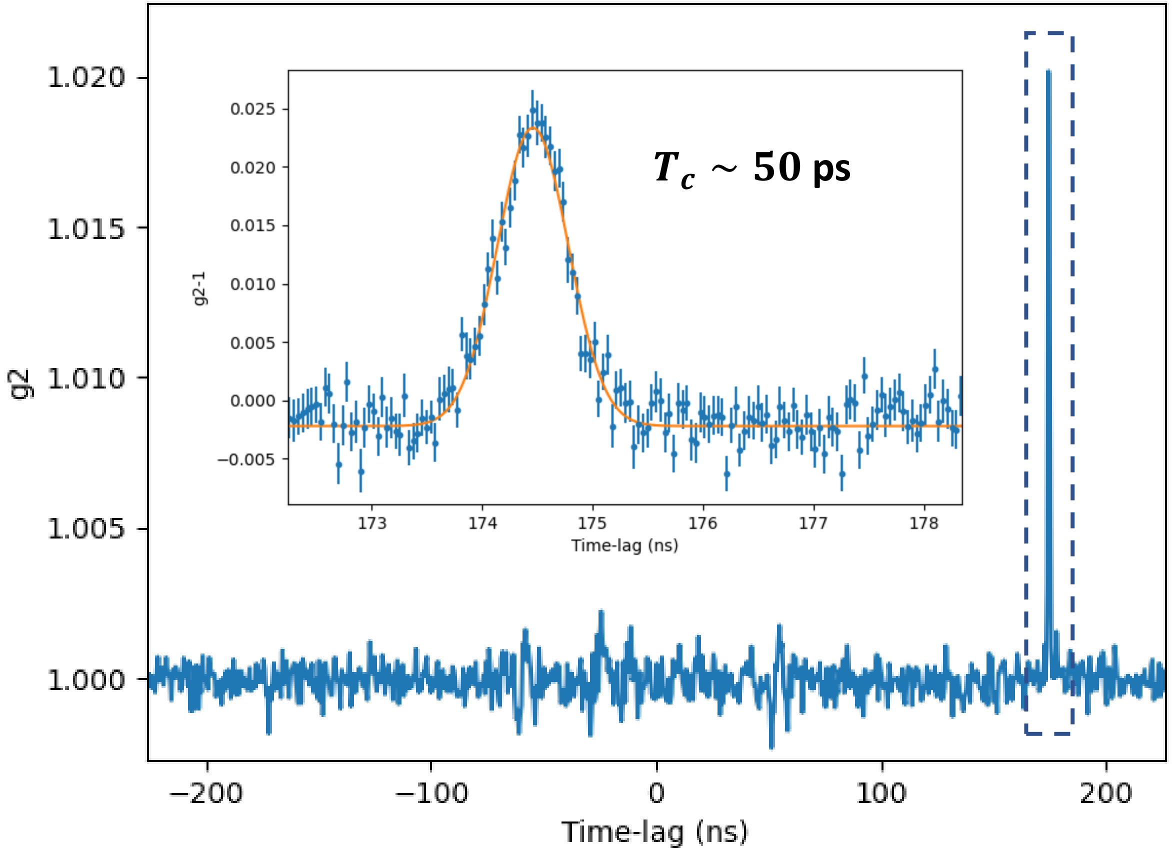
Backup

Laboratory Bench for Characterization Tests





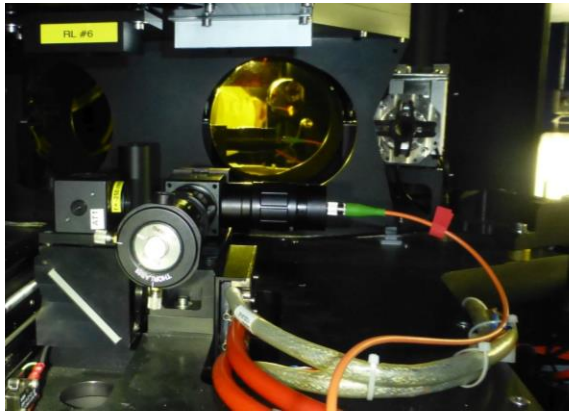
Thermal light is injected into single mode fiber and used as input to spectrometer (point-like ‘star’)



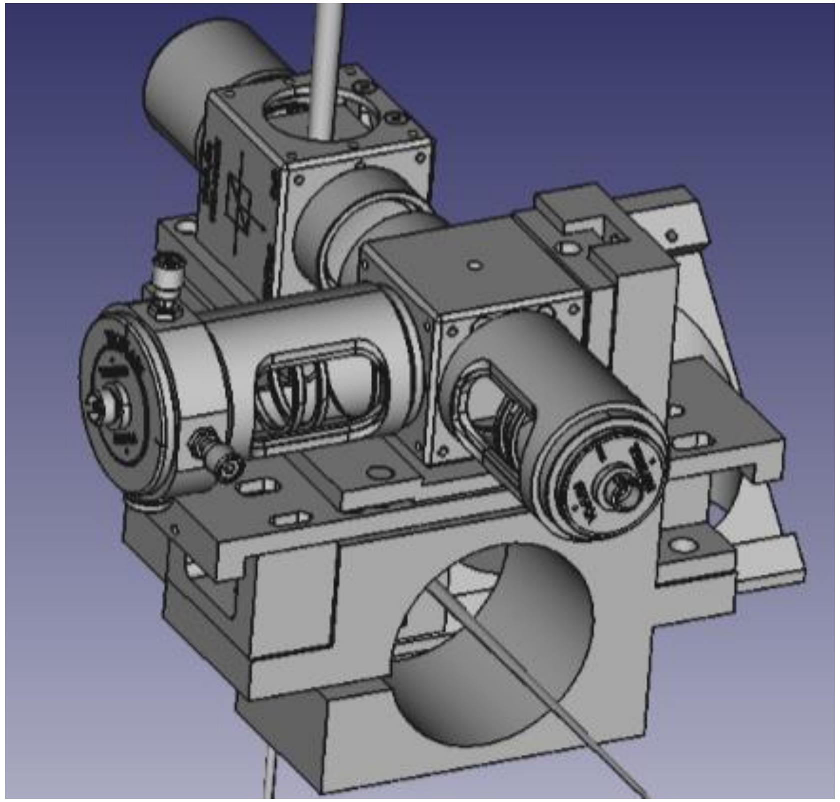
- Effective bandpass into output fiber is $\Delta\lambda \sim 0.04$ nm.
- Rotation of grating would allow one to tune to wavelengths of interest
- **In progress**: tests w/ fiber array at output of spectrograph

Observations at the VLTI

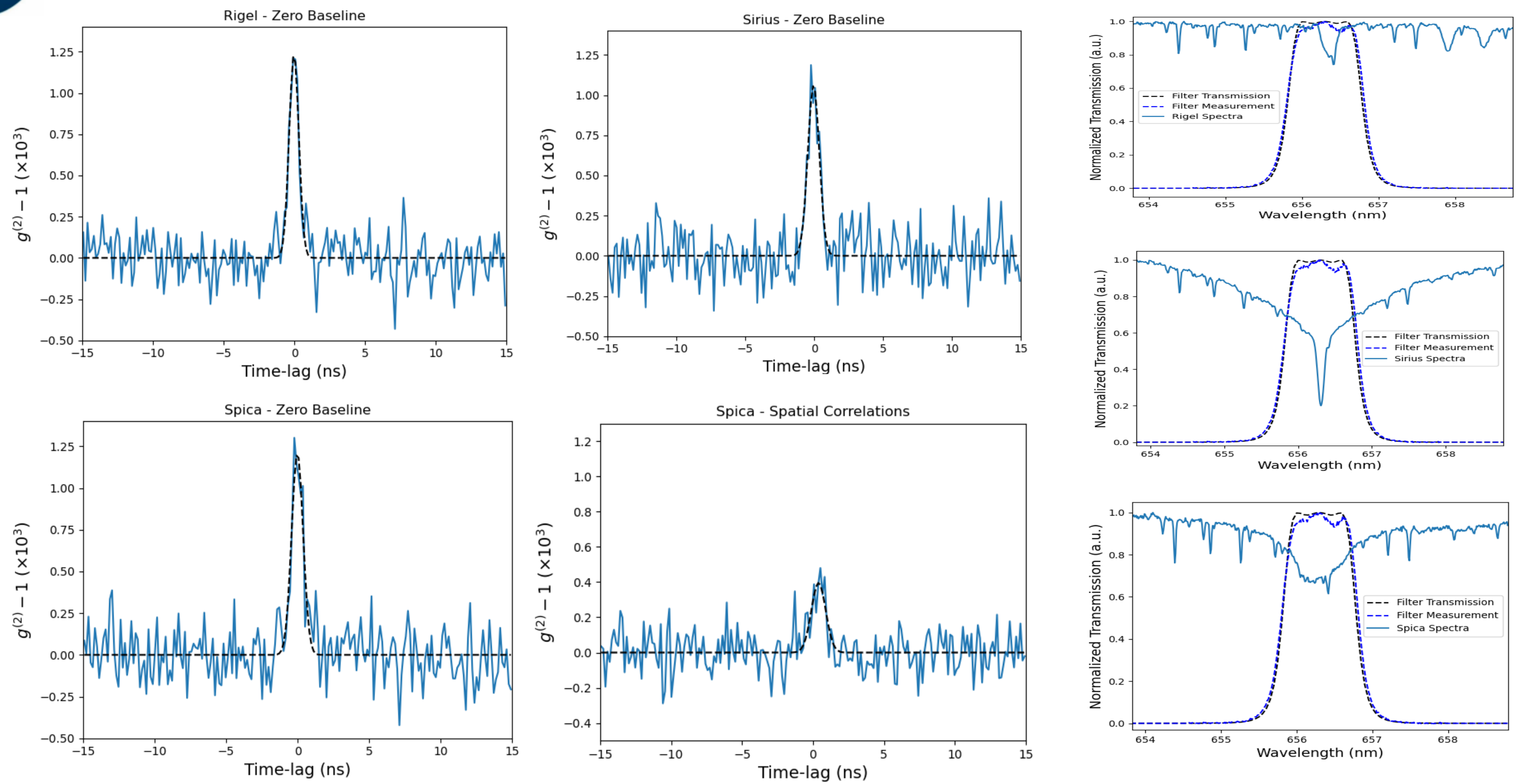
- Granted opportunity to perform technical tests with two of the VLTI-AT telescopes (49m baseline) while delay lines were in use with UTs [no impact on existing programs!]
- Introduced (removable) single dichroic in beam path and modified coupling assembly (spectral + polarization filtering + fiber injection)
- During campaign in March 2022, successfully observed single-telescope bunching peaks on 3 stars, and measured bunching peak between cross correlations of two telescopes on 1 star.



How to transport a stellar interferometer:



Recent Observations at the VLTI



Capabilities of a modern intensity interferometer

telescope area

light collection efficiency

Observing time

$$S/N = \frac{A\alpha}{\sqrt{\tau_d}} \times \sqrt{N_{ch}} \times \eta |V(d)|^2 \times \sqrt{T}$$

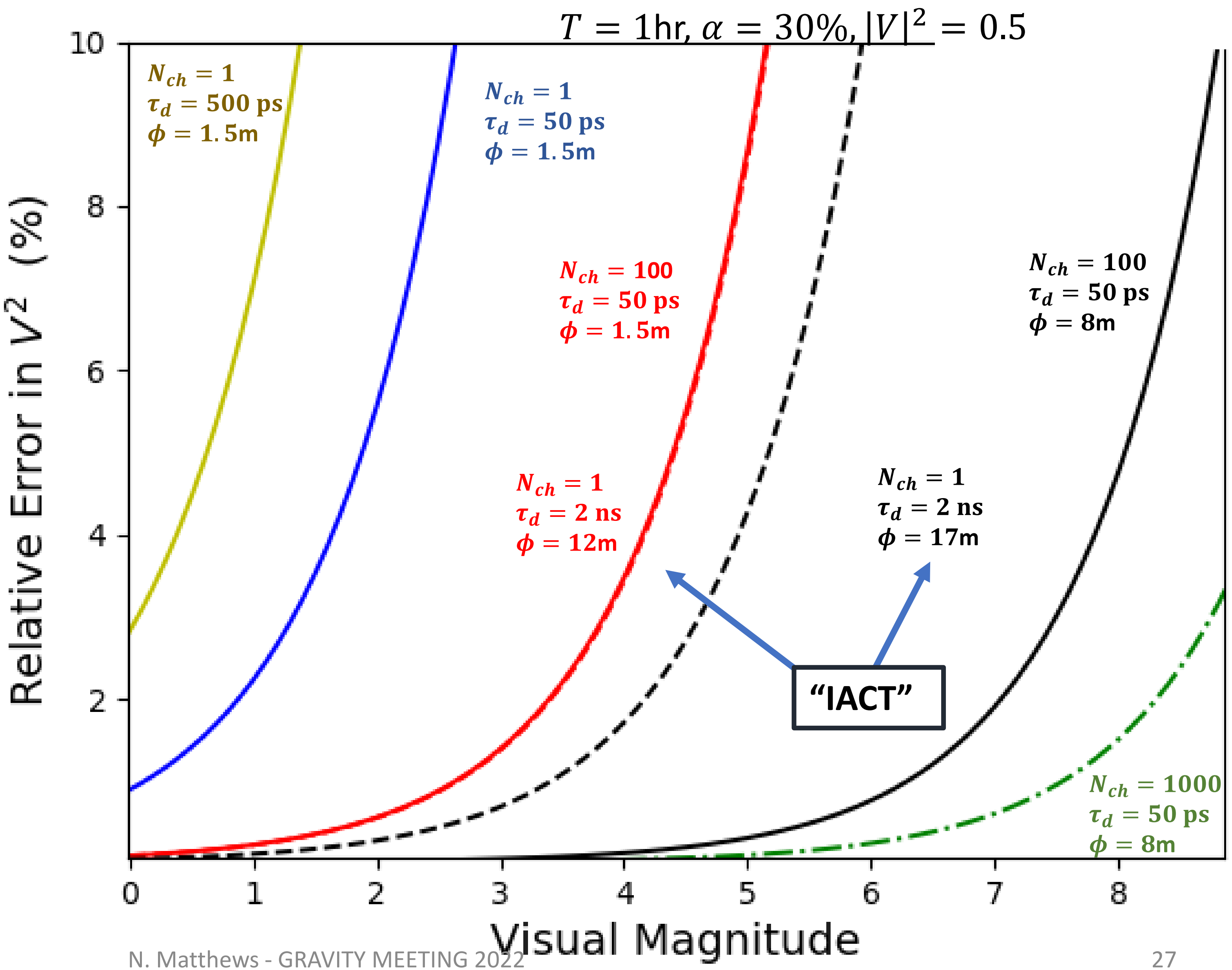
time resolution

spectral flux density

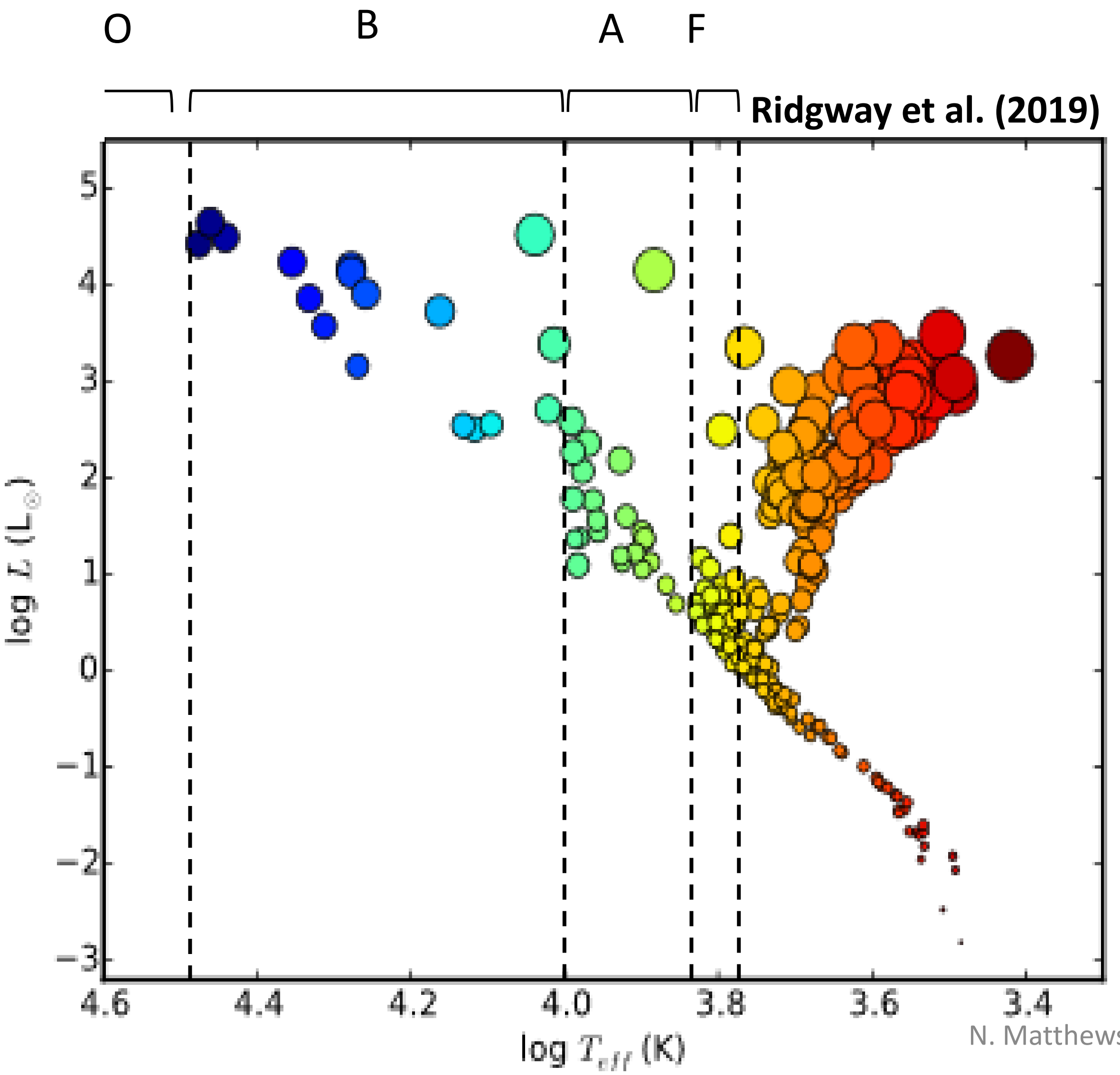
# of spectral/polarization channels

Number of stars in BSC with DEC > -20:

B Mag Range	O Stars	B Stars	A Stars
0 to 1	0	2	2
1 to 2	2	10	6
2 to 3	3	16	16
3 to 4	4	45	48
4 to 5	5	150	137
5 to 6	7	373	404



Scientific possibilities
– fundamental parameters and stellar atmospheres



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